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State-of-the-Art-Report

Improving Function Allocation for Integrated Systems Design

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This book is a compilation of the 17 papers presented during the November 1994 workshop on Function Allocation at the TNO Human Factors Research Institute, Soesterberg, The Netherlands. The workshop was sponsored by the Research Study Group 14 (RSG 14) of NATO Defense Research Group Panel 8, which in an earlier review of human engineering analysis techniques, had concluded that function allocation was the weakest of the techniques reviewed. The present workshop identified and examined central issues and techniques in function allocation (e.g., two-stage and iterative function allocation processes, reverse engineering, flexible allocation, and adaptive allocation), discussed methods for evaluating function allocation decisions, and described state-of-the-art applications of function allocation techniques.

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IMPROVING FUNCTION ALLOCATION FOR INTEGRATED SYSTEMS DESIGN

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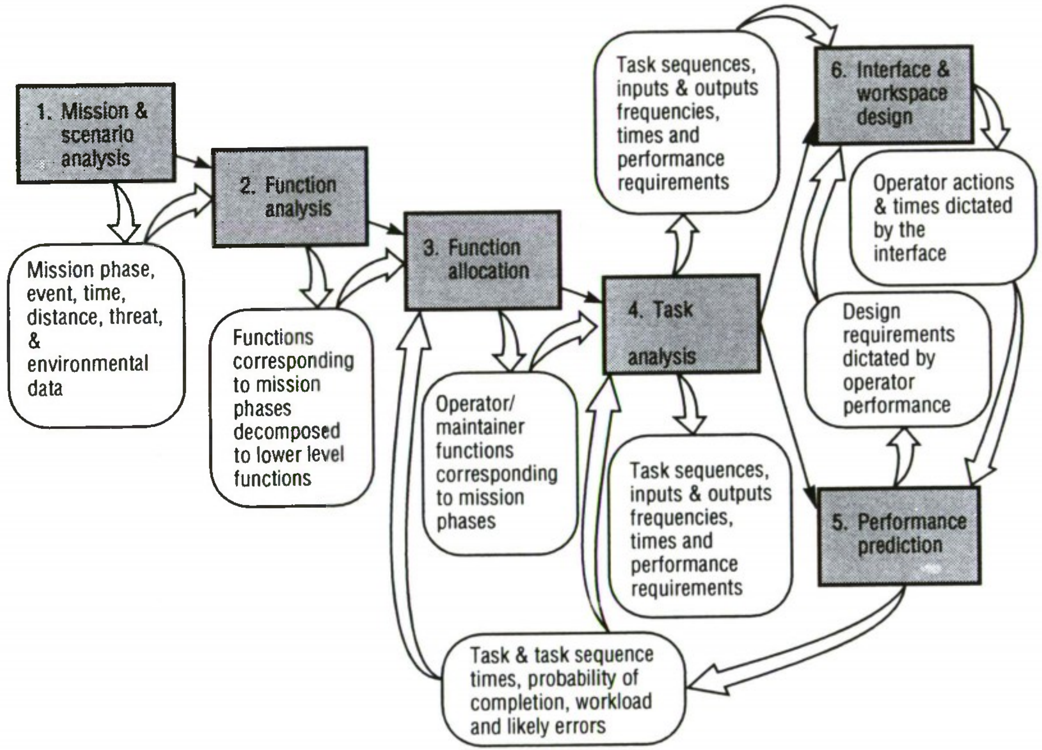
EXECUTIVE SUMMARY

Function allocation is "the process of deciding how system functions shall be implemented—by human, by equipment, or by both—and assigning them accordingly" (Beevis, 1992). Function allocation decisions define the roles, functions, and tasks performed by human operators and maintainers. Thus, function allocation is linked to issues of automation and personnel reduction, as well as to questions about human responsibility for the safe and effective operation of a system. For these reasons, some human factors specialists argue that function allocation is the most important step in human engineering. In 1992, Research Study Group 14 on Analysis Techniques for Man-Machine System Design (RSG.14) of NATO Defence Research Group Panel 8 on the Defence Applications of Human and Bio-Medical Sciences completed a review of human engineering analysis techniques (Beevis, 1992). Six main classes of human engineering analyses were identified (see figure on next page). In completing its work, RSG.14 concluded that function allocation was the weakest of the human engineering techniques reviewed and recommended that a workshop be organized to review the topic. Presentations on function allocation were solicited from the nations that participated in RSG.14, and a workshop was organized and held on November 29-30, 1994, hosted by the TNO Human Factors Research Institute, Soesterberg, The Netherlands.

The aim of the workshop was to review the need for function allocation, the maturity of available techniques, and the need for additional research in the area, as well as to make recommendations to human factors practitioners. Seventeen presentations by human factors specialists from academia, government, and industry, as well as by engineers and project managers, reviewed the state of the art in function



Six main classes of human engineering analyses.

allocation. The papers, which are reported in these proceedings, address issues of function allocation, discuss methods for evaluating function allocation decisions, and describe state-of-the-art applications of function allocation techniques. The presentations provided the basis for workshop discussions on areas where further research is required and on promising approaches to function allocation that can be used by practitioners.

Function allocation techniques that were reviewed included a simple dichotomous choice between human and machine, a two-stage allocation process, iterative modification of function allocations, and reverse engineering of operator tasks. It appeared that users compensate for the predictive weakness of available function allocation techniques by concentrating on verifying the implications of the allocation decisions for system performance or operator workload. Methods employed for this verification include computer simulations of operator workload, human-in-the-loop simulations, or trials using rapid prototypes or functional mock-ups to predict human or system performance. Examples of areas of applications that were discussed include aircraft, ships, land vehicles, and command and control systems. Some of the applications of automation reviewed permit flexible reallocation of functions depending on the operator's tasks or mission events.

The workshop drew the following conclusions:

- Problems of terminology remain, particularly when human factors specialists communicate with those in other engineering disciplines.
- Function allocation is not an isolated activity and must be incorporated in the development process early enough to influence design decisions and to permit iteration.
- No single technique is available that deals with all of the issues involved in assigning functions to humans.
- Function allocation decisions must be validated by predictions of operator workload or system performance and the allocation decisions revised if necessary in an iterative approach.
- Little research activity is devoted currently to human behavior in systems operation or to improving human factors engineering techniques.

- Several important research issues relate to function allocation, including: adaptive function allocation and the role of humans; the validity of methods for testing the implications of function allocation; and the development of a taxonomy that relates factors affecting function allocation, the problem domain, and available function allocation techniques.

REFERENCE

Beevis, D. (Ed.). (1992). *Analysis techniques for man-machine systems design* (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

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Reviewing the state of the art and identifying the need for additional research are activities needed to maintain the quality of research at an adequate level. This report is a result of such a process and is intended to illustrate the need for improving the function allocation process.

The quality of the function allocation process was discussed in the workshop on Improving Function Allocation for Integrated System Design, which followed logically from the work conducted by the NATO Defence Research Group, Panel 8, Research Study Group 14 on Analysis Techniques for Man-Machine Systems Design. The members of the research group, B. Döring, E. Nordø, D. F. Streets, R. Bost, F. R. Oberman, J.-P. Papin, H. Schuffel, and D. Beevis, prepared material and formed a committee to organize the workshop. This initiative was encouraged by Dr. A. van Meeteren, Director of Panel 8, and was supported by Dr. K. Gardner of the NATO Defence Research Section.

Special thanks are due to the following: the TNO Human Factors Research Institute, Soesterberg, The Netherlands, which hosted the meeting and whose support staff did an excellent job of providing all the necessary facilities; secretaries W. Roodenburg and N. Karsli, who did most of the work to prepare the text for publication; Dr. J. McDaniel of the US Air Force Armstrong Laboratory, who provided the 1951 report edited by Paul Fitts that originated discussion of the allocation of functions between human and machine, and who obtained permission for us to publish it; and Dr. J. E. Lincoln of CSERIAC, who served as the technical editor for this edition.

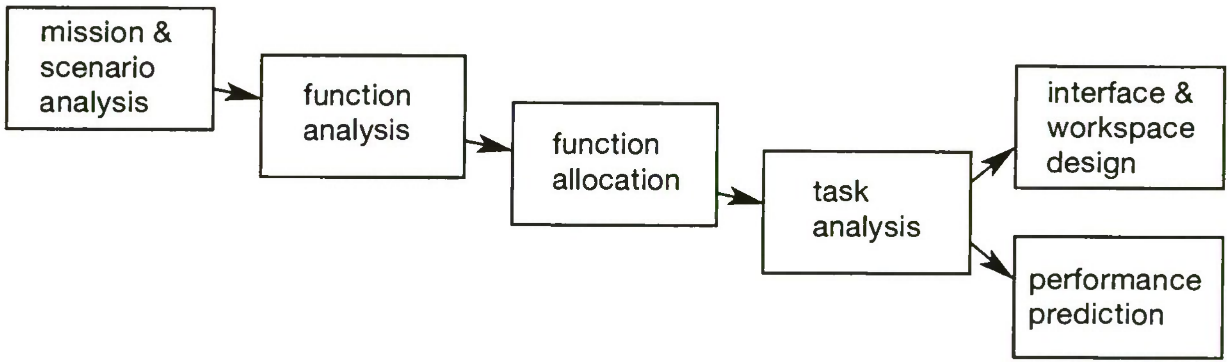
DR. H. SCHUFFEL
Chairman of the Organizing Committee,
Workshop on Improving Function Allocation for
Integrated Systems Design

INTRODUCTION

D. Beevis, P. J. M. D. Essens, and H. Schuffel

Function allocation tries to balance attempts to mechanize or automate as many system functions as possible by seeking roles and tasks for humans that make best use of their capabilities while recognizing human limitations. Typically, decisions about the roles, functions, and tasks performed by humans in a system are made implicitly in the design process through the selection or development of equipment and software. While this approach is logical, in that mechanization is usually beneficial (Chapanis, 1970), such decisions can ignore a systematic consideration of the capabilities and limitations of humans and how these affect the performance of the system. Function allocation provides the basis for subsequent human factors efforts relating to operator task analysis and description, operator performance analysis, display and control selection or design, and crew-station design, development, and evaluation. Thus, function allocation does not stand alone, but is one of several iterative stages in the implementation of ergonomics or human factors engineering in the design of human-machine systems (see figure on next page).

The concept of formal function allocation is usually attributed to the suggestion by Paul Fitts and his colleagues at the Ohio State University Research Foundation that system functions could be assigned by identifying those areas in which the human is superior to the machine and vice versa (Kantowitz & Sorkin, 1987). That seminal contribution to the topic of function allocation, comprising a chapter from a review of human engineering for air traffic control (Fitts, 1951), has been reproduced as Appendix I to these proceedings, in order to make it more accessible to the reader. By the late 1950s, the "Fitts List" approach of



Relationship of function allocation to other human engineering activities.

comparing human and machine capabilities had been incorporated into a number of human engineering guidelines (Javitz, 1956; Starkey, 1959; Van Cott & Altman, 1956). It was soon recognized, however, that functions should not be allocated on the basis of a direct comparison of human and machine capabilities, because machines are built to complement humans, not to duplicate them (Fitts, 1962; Jordan, 1963). Since then, several different approaches have been advocated (Singleton, 1974):

- conducting a comparative assessment of human and machine performance;
- performing economic cost comparisons of human and machine;
- designing tasks to exploit complementary human and machine characteristics
- grading human tasks to match individual differences;
- basing human functions on system functions and supplementing them with machines;
- permitting humans to vary their degree of participation in the system through flexible delegation of computer facilities .

Throughout the evolution of the approach to function allocation, opinions have varied widely about its utility. It has been described as "one of the first and most important problems in human-machine systems design," but one which is not helped by general statements about human and machine capabilities (Chapanis, 1965). Function allocation has also been described as a "fiction" and an "artifact," a "purely post-hoc, descriptive analysis generating few, if any, particular results" (Fuld, 1993). Such criticism may be justified in some cases. Compared with the other classes of human engineering analyses, the techniques available for function allocation have not matured: most use an ordinal level of measurement; few such analyses can be related directly to system performance requirements; and the procedures available for quality control are limited (Beevis, 1992).

At the same time, knowledge of available techniques is limited because of the way function allocation is treated in the human factors literature. Kantowitz and Sorkin (1987) have suggested that designers continue to use tables of relative merit either because they do not find criticisms of the approach convincing, or "because they are not familiar with anything better." Many human factors sources illustrate only the

earliest approach to function allocation using a tabular comparison of human and machine abilities (e.g., US Dept. of Defense, 1987). Few human factors handbooks refer to the other approaches, such as the use of orthogonal rating scales to create a two-dimensional comparison of human and machine capabilities (Price, 1985), or a five-step process for allocating functions that takes into account engineering constraints (Meister, 1985).

Given the limitations of available techniques and the lack of coverage of some of them in the human factors literature, it is not surprising that surveys show a lower level of application of formal comparative function allocation techniques than of other human engineering techniques such as operator task analysis (Beevis, 1987; 1992). One goal of the workshop at which the papers in this volume were presented was to contribute to improving the application of function allocation techniques.

As discussed by Sheridan in the keynote paper in these proceedings, the development of increasingly advanced system hardware and software makes the allocation of functions more complex than a simple dichotomous choice between human and machine. The other papers examine these problems in more detail, discuss methods for evaluating the function allocation decisions once they are made, and report state-of-the-art applications of function allocation techniques.

REFERENCES

Beevis, D. (1987). Experience in the integration of human engineering effort with avionics systems development. In *The design, development and testing of complex avionics systems* (AGARD CP 417, pp. 27-1–27-9). Neuilly-sur-Seine, France: NATO, Advisory Group for Aerospace Research and Development.

Beevis, D. (Ed.). (1992). *Analysis techniques for man-machine systems design* (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

Chapanis, A. (1965). On the allocation of functions between men and machines. *Occupational Psychology, 39*(1), 1-11.

Chapanis, A. (1970). Human factors in systems engineering. In K. B. De Greene (Ed.), *Systems psychology* (pp. 51-78). New York: McGraw-Hill.

Fitts, P. M. (1951). *Human Engineering for an effective air-navigation and traffic-control system.* Washington, DC: National Research Council.

Fitts, P. M. (1962, January). Functions of man in complex systems. *Aerospace Engineering, 21,* 34-39.

Fuld, R. B. (1993, January). The fiction of function allocation. *Ergonomics in Design, 1,* 20-24.

Javitz, A. R. (Ed.). (1956). *Human engineering in equipment design* (Electrical Manufacturing Reprint). New York: Gage.

Jordan, N. (1963). Allocation of functions between man and machines in automated systems. *Journal of Applied Psychology, 47,* 161-165.

Kantowitz, B. H., & Sorkin, R. D. (1987). Allocation of functions. In G. Salvendy (Ed.), *Handbook of human factors.* (pp. 356-369). New York: Wiley.

Meister, D. (1985). *Behavioral analysis and measurement methods.* New York: Wiley.

Price, H. E. (1985). The allocation of functions in systems. *Human Factors, 27*(1), 33-45.

Singleton, W. T. (1974). *Man-machine systems.* Harmondsworth, England: Penguin.

Starkey, D. G. (1959). *Basic human factors considerations for man-machine systems* (Report No. E9R-12114). Dallas, TX: Chance Vought Corporation, Astronautics Division.

US Department of Defense. (1987). *Human engineering procedures guide* (DoD-HDBK-763). Washington, DC: Department of Defense.

Van Cott, H. P., & Altman, J. W. (1956). *Procedures for including human engineering factors in the development of weapon systems* (WADC Technical Report 56-488). Wright-Patterson Air Force Base, OH: Wright Air Development Center.

1

ALLOCATING FUNCTIONS AMONG HUMANS AND MACHINES

T. B. Sheridan

Although automation is improving steadily, it is difficult to anticipate all the problems associated with its implementation. An approach to function allocation that combines human and machine functions seems the best solution. Several techniques used by industrial engineers are suited to the analysis of human and machine tasks. In a wide variety of systems, the human tasks are associated with supervision. A number of research topics can be identified with this type of function allocation. These topics include: questions of attention allocation and operator workload; ways to maintain situation awareness when the operator is not in the loop; the need for computers to maintain models of the user; means of sustaining operator trust in automation; and the appropriate architecture for the human-machine system.

ASSUMPTIONS

First, let us make some assumptions about human-machine function allocation (where *function* is taken here to mean essentially the same thing as *task*, though some people prefer a decomposition of mission into functions, and functions into tasks):

- Optimal allocation of functions is easy, *if* one has well-defined mathematical equations for the behavior of all human and machine functional elements, *and* an objective function that includes all salient variables is also available in mathematical form. Then all one has to do is find a simultaneous solution of these equations. This

is essentially what all formal optimization does. Unhappily, these equations are seldom, if ever, available.

- Human-machine systems (military command and control systems, domestic transportation and traffic control systems for air, sea, rail and highway vehicles, hospital systems, business and government information systems, etc.) are getting steadily more complex. (Complexity may be defined, for example, by the Kolmogorov [1987] algorithmic information measure, the shortest possible binary string sufficient to describe the parts of a system plus those sufficient to assemble the parts and perform the essential operations of the system.) In addition to this complexity is the fact that human-machine systems are getting steadily more *distributed,* meaning that multiple, isolated agents communicate over noisy, delayed channels to allocate resources held in common (Figure 1.1).
- There is no commonly accepted allocation methodology (and I'm not going to propose one).

It is an accepted fact that automation is getting better all the time. However, this means that (Kantowitz & Sorkin, 1987):

- The human must become a monitor of automation. However, it is well known that the human is a poor monitor—unless aided in certain ways that are discussed below.
- Increased automation means increased training requirements.
- Newly automated systems have bugs.
- Failure of automation leads to loss of credibility and trust.
- Designers tend not to anticipate new problems that automation brings with it (e.g., mode errors and feelings of alienation, both aspects to be discussed below).

HISTORY: COMPARISONS AND TECHNIQUES

Historically, Fitts (1951) was among the first to suggest criteria for allocating functions among people and machines. My abbreviation of Fitts' List is shown in Table 1.1.

Many others followed Fitts' lead. Meister (1971) suggested a straightforward procedure: write down all the mixes of allocation and write down all the applicable criteria. Following this, one can rank-order all

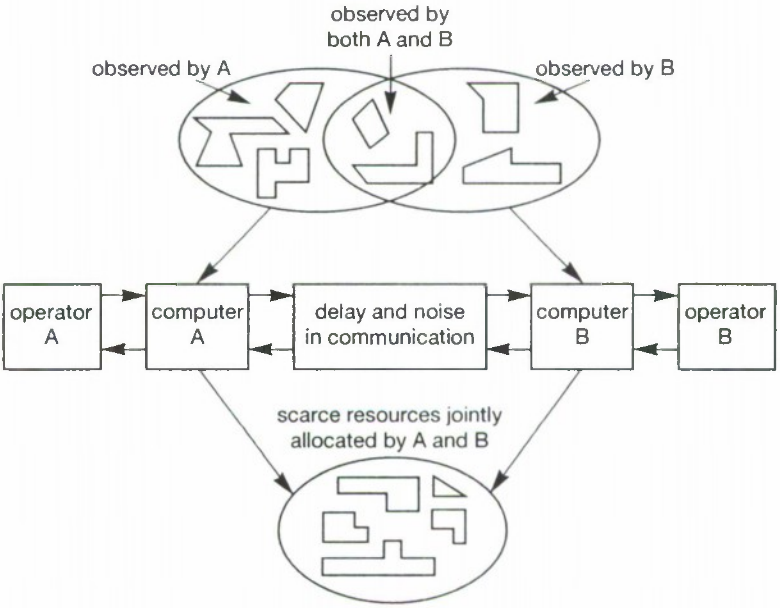


Figure 1.1. Distributed decision making. (From *Telerobotics, automation, and human supervisory control* [Fig. 3.26], by T. Sheridan, 1992, Cambridge, MA: MIT Press; after DiCesare & Desrochers, 1991. Copyright © 1992 by MIT Press. Reprinted with permission.)

Table 1.1. Fitts' List

People are better at:

- Detecting small amounts of visual, auditory, or chemical energy
- Perceiving patterns of light or sound
- Improvising and using flexible procedures
- Storing information for long periods of time, and recalling appropriate parts
- Reasoning inductively
- Exercising judgment

Machines are better at:

- Responding quickly to control signals
- Applying great force smoothly and precisely
- Storing information briefly, erasing it completely
- Reasoning deductively
- Doing many complex operations at once

combinations of allocation mix and criteria (how well each allocation meets each criterion), thus determining a rank-order score. Alternatively, one can weight the relative importance of each criterion, rate each mix on each criterion and multiply by the weight, then add up the scores for each allocation mix. The difficulties in any such direct methods include: hidden assumptions, unanticipated criteria considerations, nonindependence of criteria, and nonlinearities in importance functions (invalidating the simple multiplication of weight × rating). Price (1985, 1990) provides more recent reviews of the function allocation problem.

Combining automatic with human functions has seemed the obvious solution. After all, humans and machines seem complementary in what each does best. The cost of combining, of course, is the overhead of communicating between them (in terms of the recording and the display

and control device software and hardware to move information from one to the other).

Analysis of a given job in terms of task and/or functional elements, and their logical and temporal sequences, is amenable to many techniques that have been used by industrial engineers for years. These go by many names, but most fit relatively simply into several categories: (1) operations/flow process diagrams, similar to the now common flow charts of computer software, which show the sequencing of logic or causality and also permit feedback loops; (2) body, hand, and eye movement maps, showing what moves where in two- (or even three-) dimensional space; (3) time lines showing which human or machine element performs what action at what time, where time is a vertical or horizontal axis (time lines have difficulty with feedback loops); (4) transition frequency/association networks and matrices (Markov models); and (5) dynamic computer simulations that play out these operations in space and time on computer-graphic screens and in some cases even enable the observer to "be there" through virtual reality.

The Petri net is a relatively new version of the first category (operational/flow process diagrams) now used by manufacturing engineers to simulate which machine is performing which function when. Figure 1.2 shows an example.

Levis, Moray, and Hu (1994) make use of Petri nets to model concurrent execution of tasks by people and machines in teamwork operations and to evaluate alternative organizational and communication structures. An example is the control of aircraft from the time of leaving the gate through taxi to the point of takeoff, and the reverse, including whether a fixed allocation of terminals and gates to each ground controller is better or worse than a more flexible one that changes with time and tries to balance workload. As Levis et al. point out, however, currently available techniques do not model dynamic transitions from one allocation to another. This is a topic of current research.

SUPERVISORY CONTROL

A recent large-scale application of task analysis was made to every nuclear power plant in the United States, mandated by the government following the accident at Three-Mile Island. What was particularly interesting to the writer, who participated in many of these analyses,

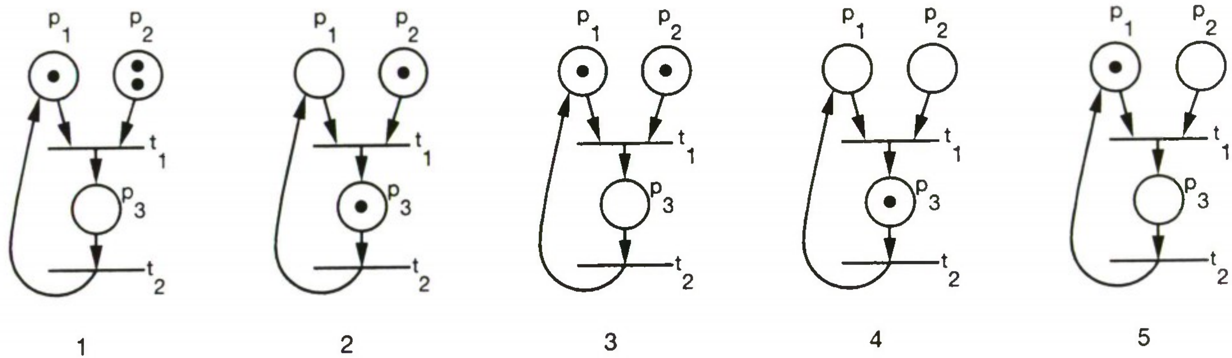


Figure 1.2. Example of how a Petri net works. *Tokens* (dots) t_i at different *places* (circles) p_j signify status of different variables in a system. For example, let tokens at p_1 and p_2 in the first diagram (1, left) signify the availability of a robot and parts to be handled, respectively, and p_3 signify that the robot is in operation. *Transitions* (bars with arrows) are events. For example, let t_1 start the robot moving a part, and t_2 end that operation. When every input place to a transition is *marked* (has at least one dot), that transition is *enabled* to fire on a clock cycle, at which time one token is removed from each input place and one token is added to each (possibly many) output place. On the first cycle 1, only t_1 is enabled. At 2, transition t_2 is enabled. At 3, t_1 is again enabled. At 4, t_2 is enabled, and the transition to 5 ends the activity. (From *Telerobotics, automation, and human supervisory control* [Fig. 1.33], by T. Sheridan, 1992, Cambridge, MA: MIT Press. Copyright © 1992 by MIT Press. Reprinted with permission.)

was the difficulty plant personnel had in considering at each task step what information the operator needed and what process variable(s) had to be controlled by what criteria. Many of the analysts could envision the tasks only in terms of what display and control devices already existed, so the task analysis was conceived in terms of what operators looked at and what they manipulated. The analysts often seemed unable to consider what alternative and potentially better ways there might be to display the required information and control the salient variables, which of course is the basic purpose of task analysis.

What has clearly been happening, ever so quietly (cynics might say insidiously) is that computers have been insinuating themselves into systems: automobiles, medical devices, industrial machinery, home appliances, and of course military systems. In these systems the computers perform data processing for sensing, providing advice (expert systems and decision aids) and decision making, in many cases closing control loops through artificial sensors and actuators without any human intervention. This moves the human to a new role of being a supervisor rather a direct or "inner-loop" controller. As a supervisor, he or she operates at a higher level than in direct manual control, or in an "outer loop." The supervisor observes computer-based displays and gets advice in the form of integrated information rather than raw data; the supervisor gives instructions (goals, constraints, procedures, suggestions) in high-level (more human) language to a relatively intelligent machine capable of understanding more complex strings of if-then-else instructions and implementing them in the physical world. The use of the "flight management computer system" in a modern commercial aircraft is a good example, but one can cite other examples in a variety of systems from hospitals to chemical plants to undersea and space robots. Sheridan (1992) provides detailed examples and theoretical discussion of supervisory control.

Figure 1.3 considers systems of various levels of automation performing tasks of various degrees of complexity (entropy or unpredictability), and indicates how some of these are undesirable (e.g., menial labor, in the lower left corner) and some are currently not possible (e.g., ultimate robot, in the upper right corner). The upper left and lower right corners offer satisfactory solutions. Supervisory control is seen as a range of technology-enabled options progressing gradually from lower left to upper right. Several examples are given.

The roles (categories of functions) of the supervisor may be

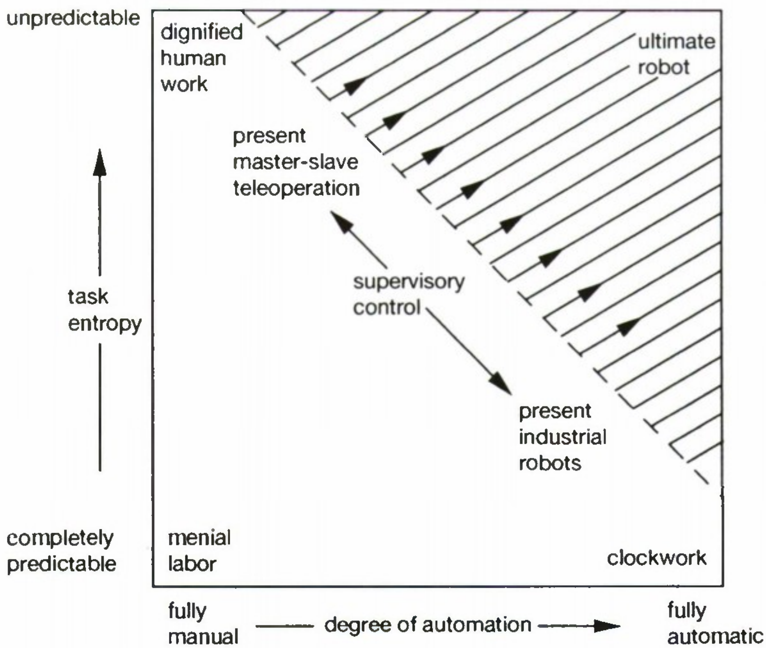


Figure 1.3. Systems of various levels of automation performing tasks of various degrees of complexity (entropy or unpredictability). (From *Telerobotics, automation, and human supervisory control* [Fig. 4.1], by T. Sheridan, 1992, Cambridge, MA: MIT Press. Copyright © 1992 by MIT Press. Reprinted with permission.)

considered to be: (1) planning, usually done off-line, with the aid of the computer and displays in a simulation mode; (2) teaching (programming) the computer with appropriate goals, constraints, procedures, and suggestions; (3) putting the system (or parts of the system) into automatic mode when ready and monitoring its operation for abnormalities; (4) intervening in the case of perceived abnormalities to diagnose failures, reprogram to alternate automatic control modes, perform direct manual control, or abort the mission, as appropriate; and (5) learning from experience, so as to improve the planning for future operations. These roles are seen in Figure 1.4 to be nested at three levels, the monitoring taking place in a tight feedback loop, the intervention

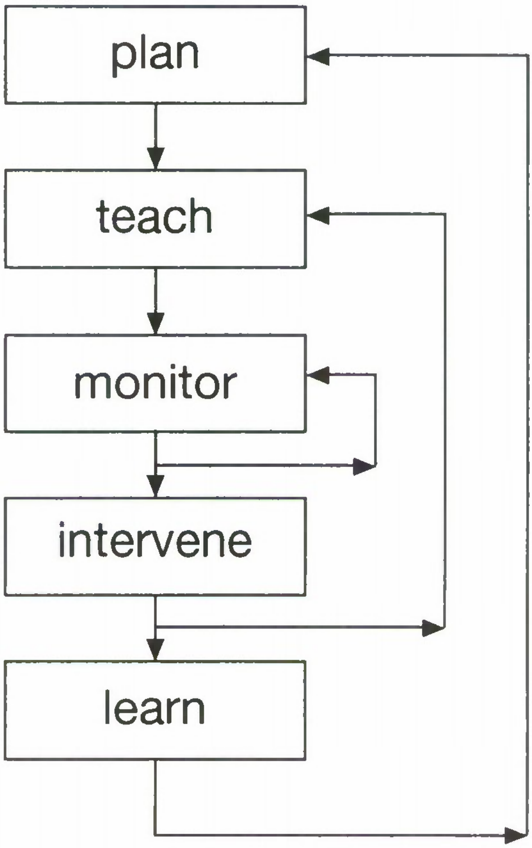


Figure 1.4. Roles of the supervisor. (From *Telerobotics, automation, and human supervisory control* [Fig. 1.2], by T. Sheridan, 1992, Cambridge, MA: MIT Press. Copyright © 1992 by MIT Press. Reprinted with permission.)

Table 1.2. Detailed breakdown of supervisory roles

SUPERVISORY STEP	ASSOCIATED MENTAL MODEL	ASSOCIATED COMPUTER AID
1. PLAN		
a) understand controlled process	physical variables: transfer relations	physical process training aid
b) satisfice objectives	aspirations: preferences and indifferences	satisficing aid
c) set general strategy	general operating procedures and guidelines	procedures training and optimization aid
2. TEACH		
a) decide and test control actions	decision options: state-procedure-action implications; expected results of control actions	procedures library; action decision aid (in-situ simulation)
b) decide, test, and communicate commands	command language (symbols, syntax, semantics)	aid for editing commands
3. MONITOR AUTOMATION		
a) acquire, calibrate, and combine measures of process state	state information sources and their relevance	aid for calibration and combination of measures
b) estimate process state from current measure and past control actions	expected results ot past actions	estimation aid
c) evaluate process state: detect and diagnose failure or halt	likely modes and causes of failure or halt	detection and diagnosis aid for failure or halt
4. INTERVENE		
a) if failure: execute planned abort	criteria and options for abort	abort execution aid
b) if error benign: act to rectify	criteria for error and options to rectify	error rectification aid
c) if normal end of task: complete	options and criteria for task completion	normal completion execution aid
5. LEARN		
a) record immediate events	immediate memory of salient events	immediate record and memory jogger
b) analyze cumulative experience; update model	cumulative memory of salient events	cumulative record and analysis

leading to reprogramming, and the learning resulting in improved planning. Table 1.2 breaks these functions into greater detail.

In Table 1.3, a ten-point scale of degrees of computer involvement is presented, as proposed by Sheridan and Verplank (1978). From considering this scale, it is clear that the amount of automation raises some serious questions.

CURRENT POPULAR RESEARCH TOPICS THAT IMPACT FUNCTION ALLOCATION

The following are some popular topics that seem particularly closely related to human-machine function allocation.

ATTENTION ALLOCATION AND MENTAL WORKLOAD

Mental workload has been a popular topic for more than a decade, but the interest today is largely in the problem of workload transients (Huey

Table 1.3. Scale of degrees of computer aiding

It is possible for system hardware and/or software to provide any of the options shown below (ANDed or ORed as noted):

1. Offer no assistance to the operator.
2. Offer a complete set of alternatives to the operator, AND
3. narrow the set of alternatives to a restricted set, OR
4. suggest one of the alternatives, AND
5. execute the suggestion if the human approves, OR
6. allow the human to veto the suggestion before automatic execution, OR
7. inform the human after execution, OR
8. inform the human after execution, if asked, OR
9. inform the human after execution, if the hardware and software decide to.
10. Decide everything without communication to the human.

Source: After Sheridan (1992).

& Wickens, 1993). Workload transients occur when automatic or semi-automatic systems go awry or fail to control unexpected events, and the human monitor or supervisor has a difficult time diagnosing the problem and taking proper action. In such cases, the workload changes suddenly from very low to very high. Measurement of these transients is particularly difficult, because most physiological and secondary-task techniques require sampling over a time period of minutes. Subjective scaling also becomes awkward when things are changing rapidly.

The need is to smooth out the pace by anticipating times of high workload and getting things set up early, for example, in getting ready for let-down and approach in landing an aircraft. Pilots call it "keeping ahead of the airplane." In emergencies, nuclear power plant operators take actions just to buy time and allow themselves a longer period to perform diagnoses and insure that their response is appropriate.

Tulga (Tulga & Sheridan, 1980) simulated and modeled such a situation with a paradigm similar to that shown in Figure 1.5, where random blocks (representing tasks) appeared on a computer screen at different distances from a vertical "deadline" on the right and moved at constant velocity toward it. The duration of the task was the block's width; its relative importance, the reward per unit time for doing it (by various means such as holding a cursor on it), was the block's height. Tulga found that subjects in this task were objective and even near to optimal in their attention and effort allocation—up to a point of high workload. Then they simply paid attention to what was nearest to the deadline, regardless of relative importance.

A related problem of particular interest is the nesting of stimulus and required response, where first notice of a required action, say A, is shortly followed by notice of required action B, where the deadline for B comes sooner than that for A. If the operator is not sufficiently reminded of A, the result is often that B is taken care of, but A is forgotten. Such nesting can sometimes be several layers deep, with disastrous results.

SITUATION AWARENESS

There is currently great interest in "situation awareness," the ability of the operator to keep track of many things at once, to integrate them, and to diagnose when events are turning abnormal or threatening. It is a problem exacerbated by automation, though possibly a problem that

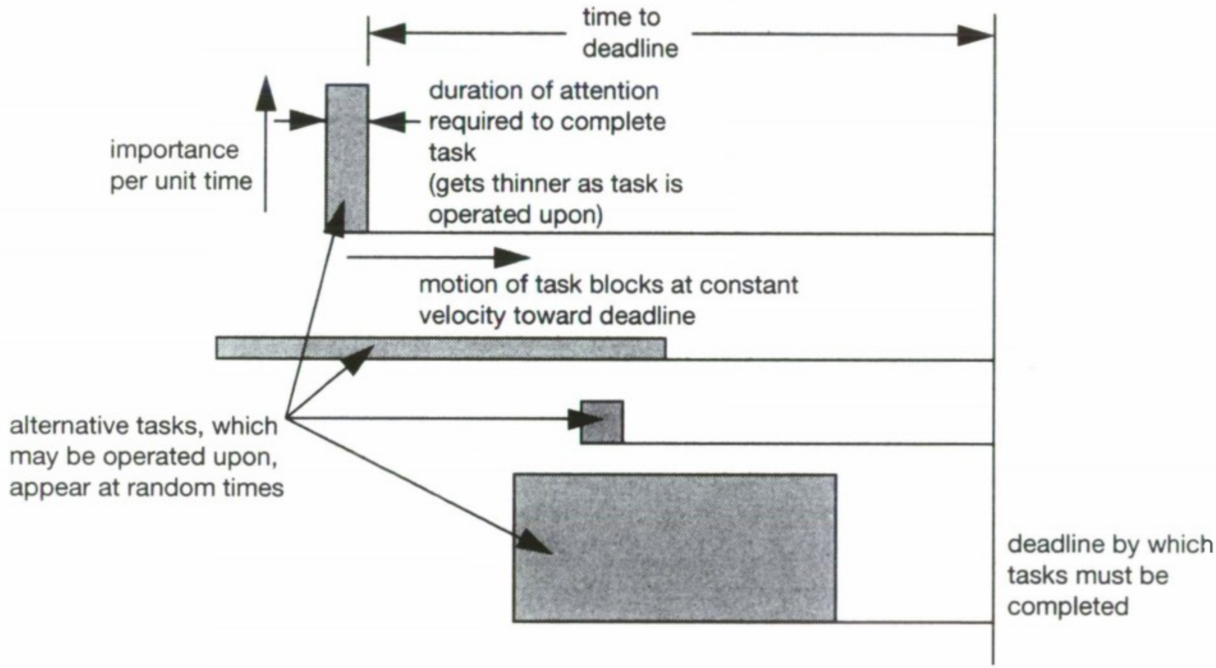


Figure 1.5. Temporal allocation of attention among tasks (Tulga experiment). (From *Telerobotics, automation, and human supervisory control* [Fig. 1.32], by T. Sheridan, 1992, Cambridge, MA: MIT Press. Copyright © 1992 by MIT Press. Reprinted with permission.)

can be helped by computers—in the form of "expert systems," decision aids, and reminders—to direct the operator's attention while monitoring. Failure to remain situationally aware has resulted in many kinds of errors, most salient among them mode errors, where operators forget what mode some automatic system has been placed into. In a well-known Airbus accident near Strasbourg, the pilot interpreted numbers on the computer display to mean one thing when they meant something entirely different; the pilot had forgotten the mode into which he had set the aircraft.

Experience in any type of human task results in behavior that becomes automatic and that does not require as much conscious deliberation as during initial learning. One might conclude that this gives the operator more time to scan and be aware of the surrounding situation, but by the same token such "downloading" of task elements and lowered self-consciousness can result in situation unawareness.

HUMANS' AND COMPUTERS' RUNNING MODELS OF EACH OTHER

Mental models have been a popular topic in cognitive psychology for a decade. The term *mental model* usually means some mental representation of objects in the external world associated with a task that can be run dynamically to predict what will happen if current conditions are extrapolated, or what would happen if certain hypothetical changes took place. There have been complaints that, while hardware—for example, the trajectory of an observed vehicle—is relatively transparent, the future action of a computer is not—the computer is a black box, and not transparent. For this reason, some have suggested that it is important that the computer inform its human operators about what it understands and what it therefore intends to do.

While the need for human communication with and modelling of the computer seems obvious, the need for the computer to have some representation or model of the human appears less obvious. However, were the computer able unobtrusively to find out and keep track of the operator's intentions, preferences, training, stress, and physical limitations, especially in times of the human's absence or illness, it might be able to make more intelligent decisions, much as would a human colleague. Figure 1.6 suggests the notion that the human and the computer keep running models of one another.

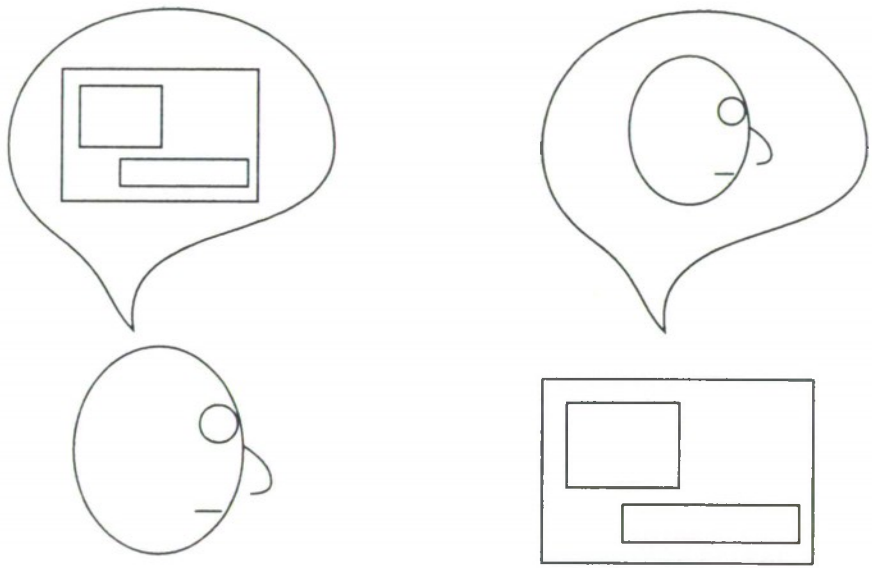


Figure 1.6. People and machines have models of each other.

ALIENATION FROM COMPUTERS AND AUTOMATION

Computers make problems for human operators not only functionally but in other ways as well, particularly when introduced abruptly and when the operator has little say in how and why the change occurred. Problems include: isolation from social contact, worry about employment, loss of skill and the associated dignity, intimidation of "big brother watching," feelings of ignorance and helplessness, reduced trust in the situation, and reduced sense of responsibility—all of which clearly diminish the ability to function. Any of these factors, particularly loss of trust, can reduce the operator's willingness to make use of computer-based sensing, advising, and automation modes that rationally could be to great advantage (Moray & Lee, 1990).

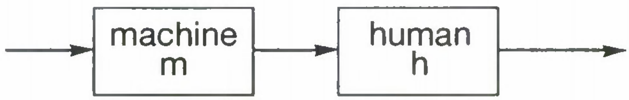
CANONICAL THEORIES OF MANAGEMENT APPLIED TO TEAMS

Allocating functions among the members of a team is a form of management (whether hidden in the system design or not), and so it is important to be aware of the various theories of management. An earlier view, variously referred to as "scientific management" or "theory X," was attributed to F. L. Taylor. Now definitely out of favor among industrial engineers, it considered the human to be a machine and sought to define and measure performance quantitatively. Of course, that is precisely what the human-machine systems approach seeks to do, but perhaps with some better appreciation of the humanistic character of the worker or operator.

Another theory, attributed to A. Maslow and F. Hertzberg and called "theory Y," begins from the assumption that any worker works for personal rewards and satisfaction, and that good management amounts to enabling and empowering workers, and motivating them to develop individual initiative and potential. A scientific function allocation has a somewhat more difficult time with this perspective and may merely regard it as unrelated or irrelevant, possibly leading to job allocations that seem rationally correct but are not satisfying and rewarding to the workers, with unhappy results.

The more recently popular "theory Z," attributed to W. Ouchi and E. Deming, calls for development of consensus—including function

Series

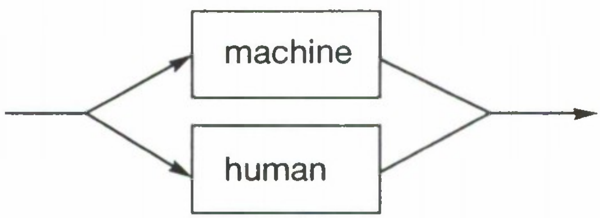


P (series combination succeeds) =
P (both m and h succeed) =

$[1-P(m)] \bullet [1-P(h)]$ if h failure independent of m,

$[1-P(m)] \bullet [1-P(h|m \text{ succeeds})]$ if h failure dependent on m

Parallel



P(parallel combination succeeds) =
P(either or both m or h succeed) =
1- P(both m and h fail) =

$1 - P(m) \bullet P(h)$ if h failure independent of m,

$1 - P(m) \bullet P(h|m \text{ fails})$ if h failure dependent on m

Figure 1.7. Reliability of functional elements in series and in parallel, where $P(x) = P(x \text{ fails})$.

allocation and reallocation—through shared goals and values, quality circles, and "total quality management." This approach militates against designing rigid systems by a priori function allocation and favors allowing enough flexibility so that allocation can always be refined by continued operator participation in problem solving and process improvement.

HUMAN-MACHINE SYSTEM ARCHITECTURES

With consideration of all of the above factors, the system engineer must return to the problem of architecture for the human-machine system, the question of how all the elements fit together and perform, and the implications of different function allocations for system performance.

Here, finally, we must decide whether, and for which functions, human and machine cooperate by "trading" or by "sharing." In trading back and forth, the human acts and then the machine acts. In sharing, the human and the machine work in parallel; either both redundantly perform the same job and these results are later compared as a check, or each does part of the job and the pieces are brought together in hopes they will fit. The reliability analyst sees these alternatives in terms of whether the elements, be they human or machine, operate in series or in parallel, and what the reliability implications are (Figure 1.7). Perhaps the simplest notion is that various intelligent (human or computer-based automatic) agents are given freedom to perform their assigned functions as they will, and only when their behaviors conflict does the supervisor step in, inhibit one (or more as necessary) and enable the others to go ahead. This approach, called by Brooks (1986) a "subsumption architecture," was shown by him to work for simple robots, but it broke down for systems faced with more sophisticated problems.

Ultimately, the function analyst must face the question of which has authority under what circumstances, human or machine. It is comforting for us to assert that the human always has final authority, but, at the same time, we readily submit to getting into elevators and pushing their buttons, thus turning authority over to those machines, or spending the night in high-rise hotels, trusting completely to the premise that strong winds won't blow them over. Figure 1.8 suggests some categories of programmed ultimate authority as a function of level of abnormality.

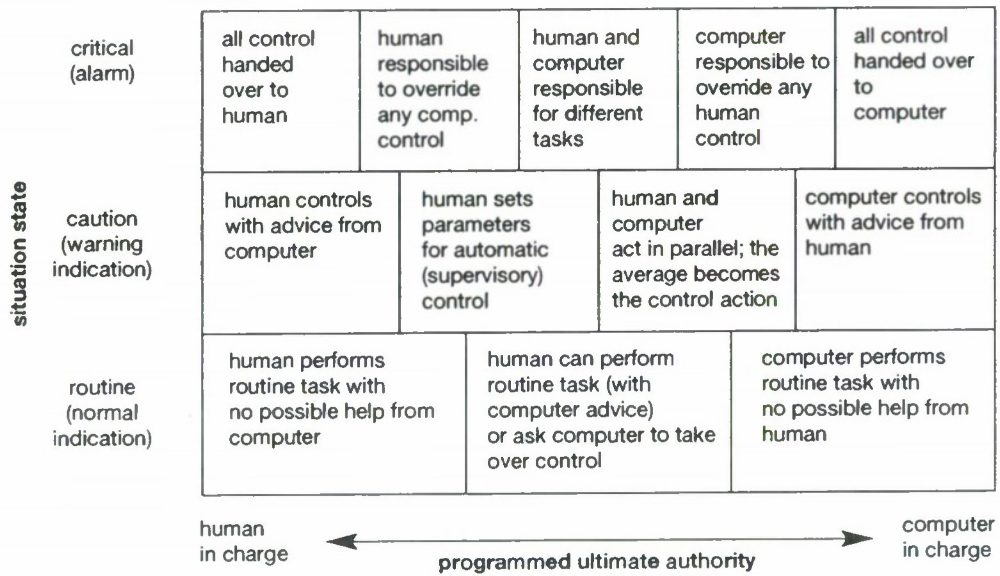


Figure 1.8. Alternate allocations of authority among human and computer for different levels of criticality.

REFERENCES

Beevis, D. (Ed.). (1992). *Analysis techniques for man-machine systems design* (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

Brooks, R. (1986). A robust layered control system for a mobile robot. *IEEE Journal of Robotics and Automation, 2,* 75.

DiCesare, F., & Desrochers, A. (1991). Modelling, control and performance analysis of automated manufacturing systems using Petri nets. In C. T. Leondes (Ed.), *Advances in control and dynamic systems* (Vol. 45). New York: Academic Press.

Fitts, P. M. (Ed.). (1951). *Human engineering for an effective air-/navigation and traffic-control system.* Washington, DC: National Research Council.

Huey, B. M., & Wickens, C. D. (Eds.). (1993). *Workload transition: Implications for individual and team performance.* Washington, DC: National Academy Press.

Kantowitz, B. H., & Sorkin, R. D. (1987). Allocation of functions. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 365-369). New York: Wiley.

Kolmogorov, A. N. (1987). *Theory of information and theory of algorithms.* Moscow: Acad. Nauka.

Levis, A., Moray, N., & Hu, B. (1994). Task decomposition and allocation problems and discrete event systems. *Automatica, 30*(2), 203-216.

Meister, D. (1971). *Human factors, theory and practice.* New York: Wiley.

Moray, N., & Lee, J. (1990). *Trust and allocation of function in automatic systems* (Report EPRL-90-05). Urbana-Champaign, IL: University of Illinois, Engineering Psychology Research Laboratory.

Price, H. E. (1985). The allocation of functions in systems. *Human Factors, 27*(1), 33-46.

Price, H. E. (1990). Conceptual system design and the human role. In H. Booher (Ed.), *MANPRINT: An approach to systems integration.* New York: Van Nostrand Reinhold.

Sheridan, T. (1992). *Telerobotics, automation, and human supervisory control.* Cambridge, MA: MIT Press.

Sheridan, T. B, & Verplank, W. (1978). *Human and computer control of undersea teleoperators.* Cambridge, MA: Massachusetts Institute of Technology, Man-Machine Systems Laboratory.

Tulga, K., & Sheridan, T. B. (1980). Dynamic decisions and workload in multi-task supervisory control. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-10, No. 5, 217-231.

2

WHY FUNCTION ALLOCATION AND WHY NOW?

J. R. Bost and F. R. Oberman

Function allocation is necessary to optimize the use of human, hardware, and/or software capabilities in advanced systems. A variety of methods have been developed for function allocation, each responding to the constraints of other methods. At the same time, developments in automation are causing ever more functions to be allocated to machines. This can provide significant cost benefits in systems such as ships, where major reductions can be made in personnel levels and, in some cases, in human errors. However, the trend to increased automation poses several questions for which research is needed, including: user trust in highly automated systems; the role of the human in future systems; dynamic function allocation; and the relationship between the computer and the human. Current approaches to systems engineering do not emphasize function allocation to personnel and/or hardware or software, but, rather, concentrate on subfunction assignment. It is suggested that a function allocation approach could be included as part of a situational assessment management process, which may include group problem solving, for formulating solutions to complex problems.

INTRODUCTION

Function allocation is the first systems engineering process that addresses functions in terms of personnel. A comprehensive and measurable function allocation process is needed now to ensure optimal use of

Table 2.1. Common form of Fitts' List

PEOPLE EXCEL IN	MACHINES EXCEL IN
Detection of certain forms of very low energy levels	Monitoring (both human and machines)
Sensitivity to an extremely wide variety of stimuli	Performing routine, repetitive, or very precise operations
Perceiving patterns and making generalizations about them	Responding very quickly to control signals
Ability to store large amounts of information for long periods, and recall relevant facts at appropriate moments	Storing and recalling large amounts of information in short time periods
Ability to exercise judgment where events cannot be completely predicted	Performing complex and rapid computation with high accuracy
Improving and adopting flexible procedures	Sensitivity to stimuli beyond the range of human sensitivity (infrared, radio waves, etc.)
Ability to react to unexpected low-probability events	Doing many different things at one time
Applying originality in solving problems: i.e., alternative solutions	Exerting large amounts of force smoothly and precisely
Ability to profit from experience and alter course of action	Insensitivity to extraneous factors
Ability to perform fine manipulation, especially where misalignment appears unexpectedly	Ability to repeat operations very rapidly, continuously, and precisely the same way over a long period
Ability to continue to perform when overloaded	Operating in environments which are hostile to humans or beyond human tolerance
Ability to reason inductively	Deductive processes

Source: US Department of Defense (1987).

advanced automation technology and an optimal role for the human in future systems.

Criteria for formal function allocation were initially developed by Paul Fitts at Ohio State University in 1951. The original Fitts' List compared the *capabilities* of human and machine. Fitts' view was that, by applying these criteria, an optimum allocation of functions between humans and machines could be achieved.

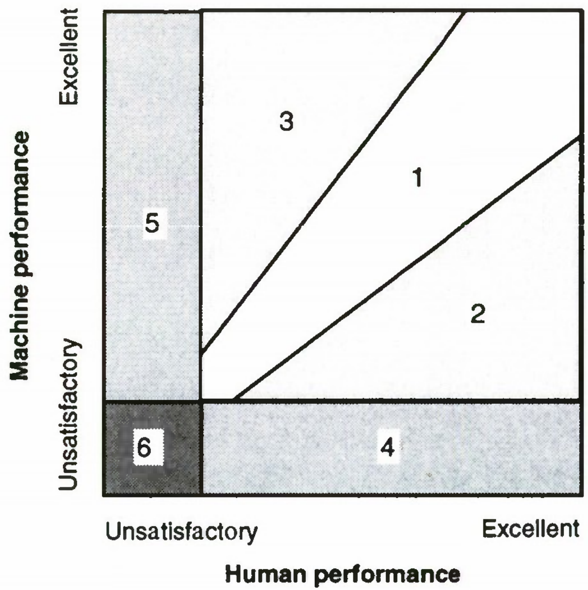
As shown in the figure in the Executive Summary, these human-machine allocations provide the baseline for subsequent efforts relating to control/display task requirements, workplace configuration requirements, workload requirements, and workstation design and development. In addition, function allocation dictates crew workload and the role of the human, thereby significantly defining human resource levels, training, and procedure requirements (Bost, Miller, & Finney, 1986).

A common form of the Fitts' List used by the US Department of Defense (1987) is shown in Table 2.1. This format again emphasized direct comparison of *capabilities*, which were then applied sequentially against defined system functions. Other versions of Fitts' List not only compare the *capabilities* of humans and machines but also the *limitations* of humans and machines.

ISSUES AND ALTERNATIVES

Function allocation criteria have continued to be developed and improved in response to problems with (1) sequential dichotomous applications of Fitts' lists (or the sequential selection of human or machine based on single capabilities or limitations); (2) assessments of human *or* machine; (3) the qualitative nature of assignments; and (4) political, managerial, financial, and performance constraints. The problem of sequential dichotomous application has been addressed by Price (1985), who proposed six different categories or regions of human-machine performance as shown in Figure 2.1.

The problem of human *or* computer allocation has been addressed by Sheridan (Table 1.3). More recently, Malone, Baker, and Oberman (1992) dealt with this issue by restating the allocation process to define the role of the human in *using* the system. This approach could be extended to define the role of the human in the *design* of the system. The qualitative nature of assignments and the need for more sophisticated



The approach recognizes six different cases of human and machine capability.

- In region 1 there is little difference in the relative capability of humans and machines, and function allocation decisions can be made on the basis of criteria other than relative performance.
- In region 2, human performance exceeds machine performance.
- In region 3, machine performance exceeds human performance.
- In region 4, machine performance is so poor that the function should definitely be allocated to humans.
- In region 5, human performance is so poor that the function should definitely be allocated to machine.
- In region 6, the functions are performed unacceptably by both human and machine, arguing for a different design solution.

Figure 2.1. Criteria for allocating functions to human or machine. (From Beevis, 1992, Fig. 3.2; after Price, 1985.)

criteria have been addressed by Beevis (1992) and by Sheridan (1994).

Kantowitz and Sorkin (1987) developed a balanced approach to deal with political and managerial constraints, as well as performance constraints. Meister (1985) has also developed a five-stage balanced approach, as shown in Figure 2.2.

Another view of function allocation is found in the approaches enumerated by R. W. Bailey (1982). Bailey categorizes three approaches to function allocation:

- a comparison of the relative capabilities of humans and machines;
- the automation of as many functions as technology permits, with only the leftover functions being assigned to the human operator;
- the use of economic allocation methods to emphasize cost constraints as a basis for the allocation.

The future of function allocation probably will be oriented toward a synthesis of the balanced approach and Bailey's three approaches, and in fact there can be synergistic benefits generated by these multiple objective approaches. The best alternative as determined from a traditional comparison may also produce the best economic benefits. One approach to ensuring that function allocation is performed in a logical manner and produces the best economic benefit (long-term and short-term benefits should be determined separately) is to do a sequential function allocation study; first a traditional study is performed, then an economic study comparing drivers and benefits is conducted using a decision/sensitivity analysis process.

COST BENEFITS

The explosion of information is leading toward the allocation of more functions to automation. The automation of functions will produce two major cost benefits: the reduction of direct personnel and personnel support costs, and the potential reduction of human error. Enormous savings potentially can be achieved in the area of personnel reduction. Within the US Navy, personnel costs are up to 50 percent of life-cycle costs, depending on the class of ship involved. Bost, Mellis, and Dent (1994) believe that cultural changes in the way we design, acquire, and operate ships will be needed to bring about revolutionary reduction in ship personnel levels. More logical, cost-effective function allocation

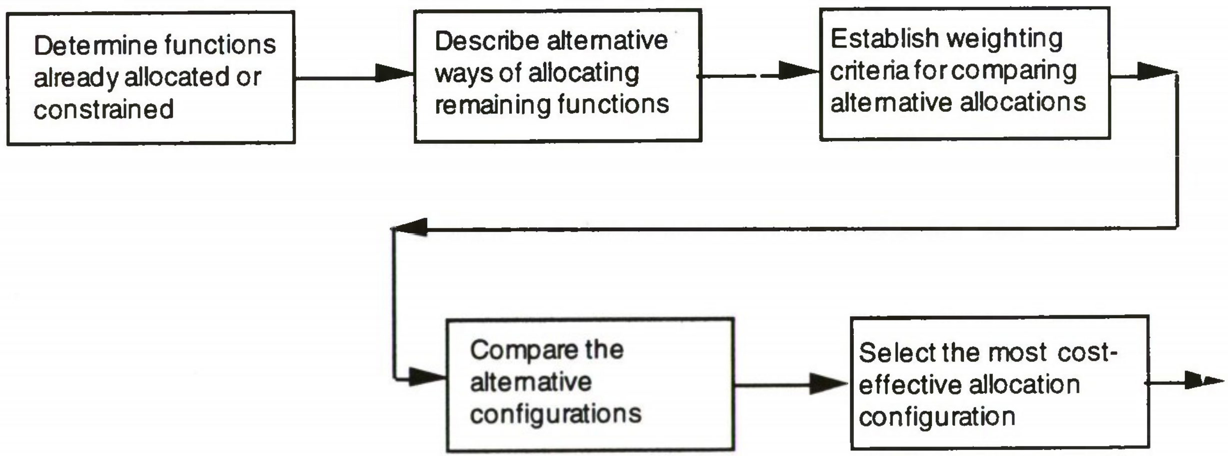


Figure 2.2. Meister's five-stage approach to function allocation. (From Beevis, 1992.)

tools are required to engineer the savings from personnel reductions. A key factor in this process is the recognition of the enormous cost of keeping personnel aboard the ship and the importance of upgrading system automation and reliability in order to keep pace with and use advanced technology. Personnel costs in the US Navy also have a ship acquisition cost component, since every person aboard ship requires an associated supportability component of 3-5 tons of ship displacement.

Another significant cost-reduction factor in automating functions is in the reduction of human error, since over 50 percent of mishaps are now classified as due to human error.

DEGREE OF TRUST IN AUTOMATION

One of the key cultural changes that will have to take place to secure the personnel and accident-reduction benefits associated with automation is a change in policies, procedures, doctrine, and perceptions with respect to trusting in automation. A first step is to produce automated equipment of sufficient reliability to engender trust on the part of the user. One discussion session at the First Automation Technology and Human Performance Conference produced an interesting analogy: in the movie *Star Trek—The Next Generation*, the android DATA is both perceived and treated as *a member of the crew*. That type of perceptual change must occur with respect to automated verses manual functions; that is, there must be enough trust in the built-in reliability and performance of the automatic system to allow it to perform ship operations and missions. This will have profound and significant changes on doctrine and procedures, on the role of the human, and on the redefinition of responsibility.

On the other hand, humans must not become so complacent in using automation that normal monitoring does not take place. The recent Aeroflot Airbus crash in which the pilot, who was found in the passenger compartment, left his son (who managed to disengage the autopilot) in the cockpit, is an example of poor judgement engendered by complacency with respect to the automatic pilot.

The answer is that the general situation should determine the degree of automation; for example, chemical process control already has high degrees of automation. Yet in cases that are not time dependent, the human will still play the major role of decision maker/monitor.

AUTOMATION TODAY

One of the reasons automation is able to provide these cost benefits is the current state of the art and expected near-future development in this technology. Automation has advanced a long way since Fitts' initial concept was developed—a PC is now more powerful and faster than a main frame in 1951. Not only has the technology changed to allow the implementation of reduced-manning concepts that were only advocated in the 1950s and 1960s, but a new generation of computer-literate personnel will very shortly be available to implement the decisions and actions of the future. They will think in terms of the computer to accomplish these ends.

Not only has automation technology enhanced the speed and performance of functions, it has also provided the same benefits to the development of human factors tools, including those used for function allocation. Tools have been developed for performing function allocation for total system design and for system reengineering (Malone, 1992; Chap. 13 by Swartz & Wallace in this volume). The capability to carry out computer-assisted function allocation can now enable this human-system engineering process to be performed and the results of the analyses used within the time constraints of project design phases. Moreover, when function allocation is performed in the conceptual phases of acquisition, data storage by electronic means, such as on CD-ROM, allows the iterative updating of information to proceed in a cost-effective, timely manner.

FUTURE RESEARCH QUESTIONS

There are questions that come with the opportunities which will be available in implementing the function allocation methodologies of the future. Among the most important questions are:

- Should a review of earlier versions of Fitts' lists be undertaken to ensure that new technology has not altered the original comparisons?
- What is the role of humans to be in future systems? Is the human only to be a system monitor, while machines perform most functions? If so, how and by what criteria do humans override computer operations?

- How does the human decide when there is an automation malfunction? How will we ensure that systems will give the human operator adequate time both to perceive a malfunction and to initiate corrective action?
- If a human is in control, should the decision as to when to shift to automatic control be standardized in doctrine or left open to individual judgement? What should be provided in the way of decision aids? Should we ever let the system be involuntarily taken over by automation? What would be the criteria for allowing automation to take control? Should the operator be notified when automation has taken control?
- Function allocation will become more dependent on expert (opinion) systems in the future. What studies are now taking place with respect to validation and evaluation of results? What criteria have been established to determine the value of proposed function allocation tools? Has a consideration of return on investment been factored into current tool development?
- There are cultural differences in how automation is currently applied (Tefler, 1994). The European A320/340 Airbus is flown with different degrees of manual and automatic control, depending on the country and airline operating it. Are cultural differences and diversity useful or should the degree of automation and the decision on when to use it be controlled or standardized?
- How should the problem of keeping controllers/decision makers proficient in manual (backup) operations be handled?
- Should automatic systems take over from a human operator in periods of high workload? (This assumes workload sensors will be required.) When should control be transferred back? Should this be a human decision or should it be performed automatically? Should dynamic task automation (Hilburn et al., 1994) be considered?
- What status information should be displayed and how should it be displayed? Should it be under human control or should some status information be displayed automatically? If it is displayed automatically, what should be displayed and when should it be displayed?
- For some new display systems, new cognitive skills and cognitive pathways are required. What is being done to ensure that overall

human-machine operational processing is improved with respect to accuracy and time?

- How do we evaluate alternatives? What criteria should be used? Can these criteria be further used to generate deterministic and/or probabilistic performance parameters? Can we now evaluate overall reliability of the human-machine system by using decision analysis and sensitivity analyses?

SYSTEMS ENGINEERING CONCERNS

Although universities include human factors as an essential component of systems engineering and include function allocation as a fundamental analytical process, this view of function allocation has *not* been incorporated in recent proposed revisions to the US military standard *MIL-STD-499B, Systems Engineering* (US Dept. of Defense, 1994). There seems to be confusion between the two analytical processes of requirements allocation, which matches requirements against functions, and function allocation, which matches functions against human-machine capabilities and limitations. Because of this confusion, no attention has been given to human-machine comparisons. The need for human-machine analysis must be reiterated in this primary systems engineering document.

FINAL PARADIGM—SITUATIONAL MANAGEMENT

There has been much discussion of situation awareness with respect to decision making and control. What is really needed is to manage decision making and control with respect to two variables: available time and problem complexity. Moreover, problem solving should not only involve human and computer, it should also involve *humans* and *computers*. This gives the added benefit of group participation in complex problem solving, a benefit that has been documented since the 1960s (Oberman, 1964) and is a recurrent theme in aircraft and commercial ship management today (Foushee & Helmreich, 1988). A general view of situational decision management (SDM) is shown in Figure 2.3. Figure 2.4 presents an example of situational assessment. This management model emphasizes the ultimate decision making, by humans *and* computers, to be used when appropriate and still considers the

DECISION/ACTION AGENT	TIME AVAILABLE	COGNITIVE DIFFICULTY
1. Personnel and software	Long	Complex
2. Individual manager and software	↕	↕
3. Software	Short	Simple

Figure 2.3. Situational decision management.

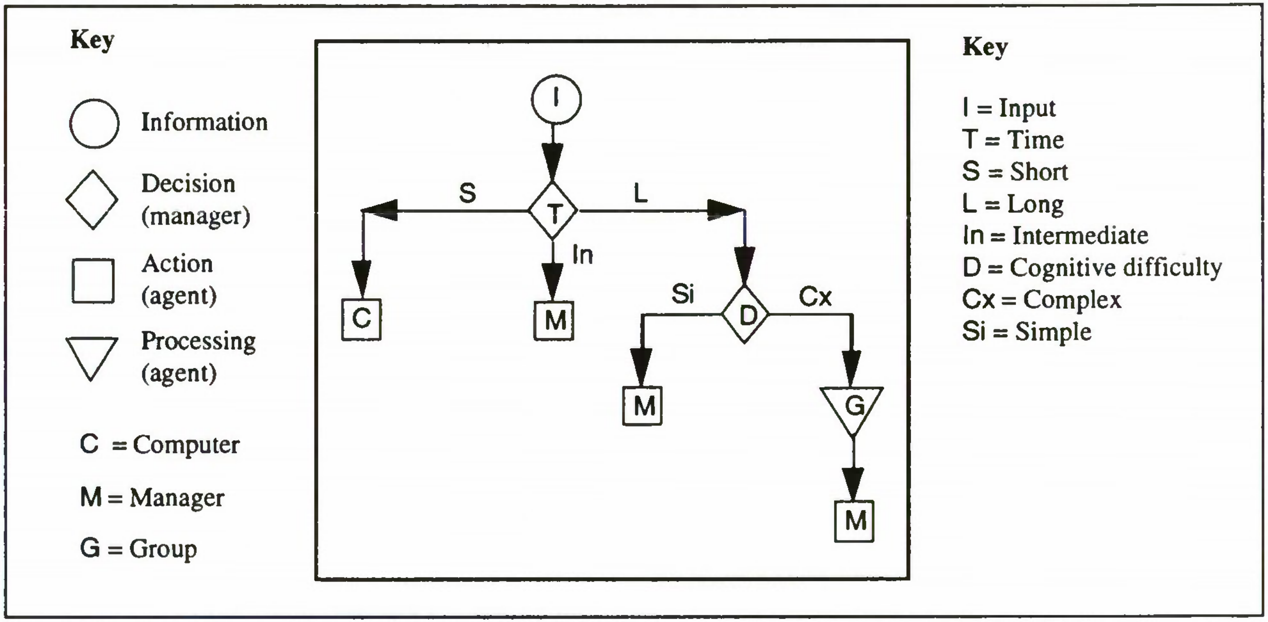


Figure 2.4. Example of situational assessment.

paramount constraint of time as an overriding factor. Figure 2.4 shows a recommended approach based on relevant research. It is, in effect, a decision aid. In this model, time is the first decision point. If time is short (critical), then action should be allocated to the preprogrammed computer (automation). If an intermediate time exists, the manager should initiate the action to be taken (which can include activating a computer response). If the time available for the decision is long, then the decision manager should first assess whether the problem is simple or complex. If the problem is simple, then the manager should initiate the action to be taken (which again can include activating a computer response). If the problem is complex, the manager should discuss and evaluate solutions with an appropriately chosen problem-solving group or team and then initiate actions to be taken by individual members of the group and/or software.

SUMMARY

WHY DO FUNCTION ALLOCATION?

We need to do function allocation in order to maintain logical and rational control of the human-computer process. We need to do function allocation to ensure that the role of the human in future systems is well defined and well understood. We need to do function allocation to provide the cost benefits of rational automation processes.

WHY NOW?

We need to do and improve function allocation now because we are at a technological crossroads engendered by the capabilities of software to reliably take over processes previously performed by humans. We need to do and improve automated function allocation processes now in order to be a part of this automation and information revolution. We need to make sure that function allocation is understood and set forth as part of systems engineering in key military and commercial standards because systems engineering is and will be a major controller of how future automation is performed. Human systems engineering *must* remain a major player in the systems engineering process.

REFERENCES

Bailey, R. W. (1982). *Human performance engineering: A guide for systems designers*. Englewood Cliffs, NJ: Prentice-Hall.

Beevis, D. (Ed.). (1992). *Analysis techniques for man-machine systems design* (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

Bost, J. R., Mellis, J., & Dent, P. (1994). *Is the navy serious about reducing manning on its ships?* Paper presented at the Association of Scientists and Engineers Technical Symposium, Arlington, VA.

Bost, J. R., Miller, G. E., & Finney, J. W. (1986). *Integrating human engineering into the ship design process.* Paper presented to the Society of Naval Architects and Marine Engineers, New York Metropolitan Section, Jersey City, NJ.

Foushee, H. C., & Helmreich, R. L. (1988). Group interaction and flight crew performance. In *Human factors in aviation* (pp. 189-227). New York: Academic Press.

Hilburn, B., Mouloua, M., & Parasuraman, R. (1994). *Adaptive training in automated systems.* Paper presented at the First Automation and Human Performance Conference, Catholic University, Washington, DC.

Kantowitz, B. H., & Sorkin, R. D. (1987). Allocation of functions. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 365-369). New York: Wiley.

Malone, T. B., Baker, C. C., & Oberman, F. R. (1992, May). Reverse engineering allocation of function requirements methodology, REARM. In *Minutes of the twenty-eighth meeting of the Department of Defense Human Factors Engineering Technical Group*. New Orleans, LA.

Meister, D. (1985). *Behavioral analysis and measurement methods.* New York: Wiley.

Oberman, F.R. (1964). *Learning in small groups under fixed and variable ratio reinforcement.* Unpublished master's thesis. Loyola University, Chicago, IL.

Pew, R. A. (1994). Introduction to the concept of situation awareness. In *Situational awareness in complex systems* (pp. 17-19). Daytona Beach, FL: Embry-Riddle Aeronautical University Press.

Price, H. E. (1985). The allocation of functions in systems. *Human Factors, 27*(1), 33-46.

Sheridan, T. B. (1994). *Automation and human performance: Dreams and reality.* Paper presented at the First Automation and Human Performance Conference, Catholic University, Washington, DC.

Tefler, R. (1994). *Approaches to learning by airline pilots.* Paper presented at the First Automation and Human Performance Conference, Catholic University, Washington, DC.

Tenney, Y. J., Adams, M. I., Pew, R. A., Huggins, W. F., & Rogers, W. H. (1992). *A principled approach to measurement of situational awareness in commercial aviation* (NASA Contractor Report No. 4451). Langley Field, VA: Langley Research Center.

US Department of Defense. (1987). *Human engineering procedures guide* (DoD-HDBK-763). Washington, DC: Department of Defense.

US Department of Defense. (1994, July). *Systems engineering* (MIL-STD-449B [Draft]). Washington, DC: Department of Defense.

Wallace, D. F., & Swartz, M. L. (1994). *Workload analysis and task reallocation for re-engineering manual/supervisory control systems.* Paper presented at the First Automation and Human Performance Conference, Catholic University, Washington, DC.

3

FUNCTION ALLOCATION AND MANPRINT[1]

M. K. Goom

The Manpower and Personnel Integration (MANPRINT) program provides a framework for applying function allocation in the development of modern defense systems. Within the MANPRINT framework, the contractor's task is to determine which of the feasible design solutions best matches the skills, abilities, aptitudes, knowledge, etc., of the users. Experience in formulating a practical approach to MANPRINT suggests several guidelines for function allocation. Function allocation is found to apply throughout the development cycle rather than as a clearly identifiable event. The human characteristics that are normally cited in illustrations of function allocation in human factors texts are usually so general that they do not help in a practical way. It is often very detailed information on the user's capability and existing knowledge base that will determine if the task would be better handled by human or by machine. The allocation of functions on the basis of job design and resulting workload appears to be more appropriate. Workload prediction tools that can be used early and quickly are required. A short-term aim has been to develop a register to capture the factors and the thinking that goes into allocating tasks to either human or machine. A long-term aim is to produce a task database that carries information on learning difficulty, retention times, etc., with links to specific user populations.

INTRODUCTION

This paper seeks to link the function allocation process to some of the lessons that have been learned during the development of the MANPRINT (Manpower and Personnel Integration) program within the Dynamics Division of British Aerospace.

Function allocation has been identified as the weakest technology in the process of integrating users into defense systems. This paper attempts to show that, in the real world, function allocation (and MANPRINT) takes place throughout system development; it does not exist as a discrete entity and, because of this pervasive nature, does not attract the attention it should from system designers. Many of the practical considerations relate to the constraints on time and funding that often accompany the commercial development of a defense system. These constraints cause a focusing of effort on those aspects that can be shown to have a cost benefit, are likely to produce results in the correct time frame, and, most importantly, can be defined clearly enough to appear in a work breakdown structure (WBS). An additional practical consideration is the problem of obtaining an adequate definition of the end users from the customer.

The traditional Fitts' List approach to function allocation taught in many human factors courses is hardly sufficient for complex weapon systems. Ergonomists must recognize these practical difficulties and devise methods that are relevant to modern needs and can be applied throughout the development process. MANPRINT has the same aims as function allocation in that it seeks to recognize the characteristics and capabilities of the constituent components of the system. MANPRINT's strength is the concern it focuses on the detail of the end user. The practical methodology British Aerospace has produced in response to the MANPRINT requirement provides useful indicators for the function allocation activity.

This paper does not cover the very interesting and important areas of allocation between teams of individuals and machines (Stammers & Hallam, 1985). In the next section, the MANPRINT program is briefly described to identify the contractor's tasks within system development. This section also discusses where the allocation activities occur within the system design life cycle. The third section examines the commercial constraints on projects that may compromise the optimal allocation of functions among hardware, software, and the users. The difficulty that

many system developers have in separating mission analysis, functional analysis, and task analysis is considered in the fourth section. This uncertainty with terminology only increases the problem of applying function allocation. The fifth section considers the allocation process itself, examines where the weaknesses of the traditional methods occur, and describes a possible approach that has resulted from producing a practical MANPRINT implementation. The use of adaptive or dynamic function allocation and some of the benefits and concerns are briefly examined in the sixth section. The seventh section contains the author's suggestions for next steps to improve the allocation of functions during practical system development. Finally, the last section draws some conclusions as to why function allocation is difficult to identify in a practical development project and suggests possible ways it could be made more efficient.

THE MANPRINT PROGRAM

MANPRINT is an acronym for manpower and personnel integration (Booher, 1990). Essentially, it means ensuring that the design is optimized for the people who will have to operate, maintain, and support the hardware and software portions of the system. MANPRINT or human-systems integration or human factors integration program or liveware are about designing for the true end users. For these reasons, the allocation of functions and tasks to either human or equipment is at the very core of MANPRINT.

THE HISTORICAL REASONS FOR MANPRINT

The US MANPRINT program came into being during the early 1980s. It was born out of a realization that many of the high-tech systems that were being delivered were not performing as designed. The development emphasis had been on the technology, with the implicit assumption that suitable people could be recruited or trained, which turned out not to be true.

Complex systems were supposedly simplified by the use of automation. Those functions that could easily be automated became the province of the machine, with little thought that the remaining functions did not constitute logical "jobs" for the users. Indiscriminate automation often masks the underlying structure of the system from the users, caus-

ing learning difficulties and poor performance. Function allocation had usually been applied, but in a mechanistic way, with the allocation being based on isolated tasks.

WHO IS THE USER?

The cost of adapting users to the system through training is usually far greater than the cost of changing hardware and software during the early stages of system development. MANPRINT recognizes this via the Target Audience Description (TAD). To ensure usability, it is important to understand and quantify those capabilities and characteristics of the user that are going to impact total system performance.

Knowing that the user is a human being is not really sufficient. The characteristics that must be known to guide successful system development include: aptitude for various tasks, existing knowledge, organizational structure, etc. Where real defense systems are concerned, it is often very detailed information on the user's capability and existing knowledge base that will determine if the task would be better handled by human or machine. The characteristics that are normally cited in illustrations of function allocation in human factors texts are usually so general that they could not help in a practical way. Also, most of the examples of allocation have centered around the pilot's cockpit and air traffic controller's workstations. From a MANPRINT standpoint, the user variability to be accommodated in the design of such systems is small compared with that which may be required for an infantry command system to be exported throughout the world. It is interesting to note that both of the former user groups are subject to very stringent selection criteria.

WHAT IS THE USER'S JOB?

One of the principal lessons that has emerged from the application of MANPRINT has been the need to identify the jobs of the users. This must include *all* the component tasks that the users will have to undertake, not merely on the system under development, but also on other systems that they will be required to operate, as well as tasks that originate from their day-to-day military duties. In many cases, the allocation of system tasks to human or machine is governed by the task (and work) loading imposed by activities outside the immediate system.

Mechanisms are having to be found that can identify and communicate these outside tasks to the system developers in industry in a meaningful way.

WHAT IS THE CONTRACTOR'S TASK?

The contractor's task (Figure 3.1) consists, first, of analyzing the customer's requirement and translating it into a mission analysis and a description of the users that the customer will have available. The latter is referred to as the Target Audience Description (or TAD). The contractor's task then consists of generating options that can match the mission requirements and analyzing the tasks that those options entail. The contractor's MANPRINT task is to determine which of the feasible solutions best matches the skills, abilities, aptitudes, knowledge, etc., that the target audience possesses. It is during this matching that the allocation process is used to balance the tasks within each option between human and machine.

TIMETABLE FOR MANPRINT (FUNCTION ALLOCATION)

When MANPRINT was first introduced to British Aerospace, many people expected to be able to pick up a MANPRINT package and apply it once they had designed their system. This was the way human aspects such as training had been handled in the past. A major part of implementing MANPRINT within industry has been explaining to system developers that MANPRINT needs to be applied throughout the whole of the development life cycle. The major input, however, should be in the early phases of concept, feasibility, and project definition (in UK terminology). Changes to the allocation of tasks after project definition are usually fixes to cover technological shortcomings.

COMMERCIAL CONSTRAINTS

The allocation of tasks and functions between human and machine does not take place in a vacuum. The process of allocation has to recognize that certain tasks may be allocated as a result of constraints that range from technology to politics.

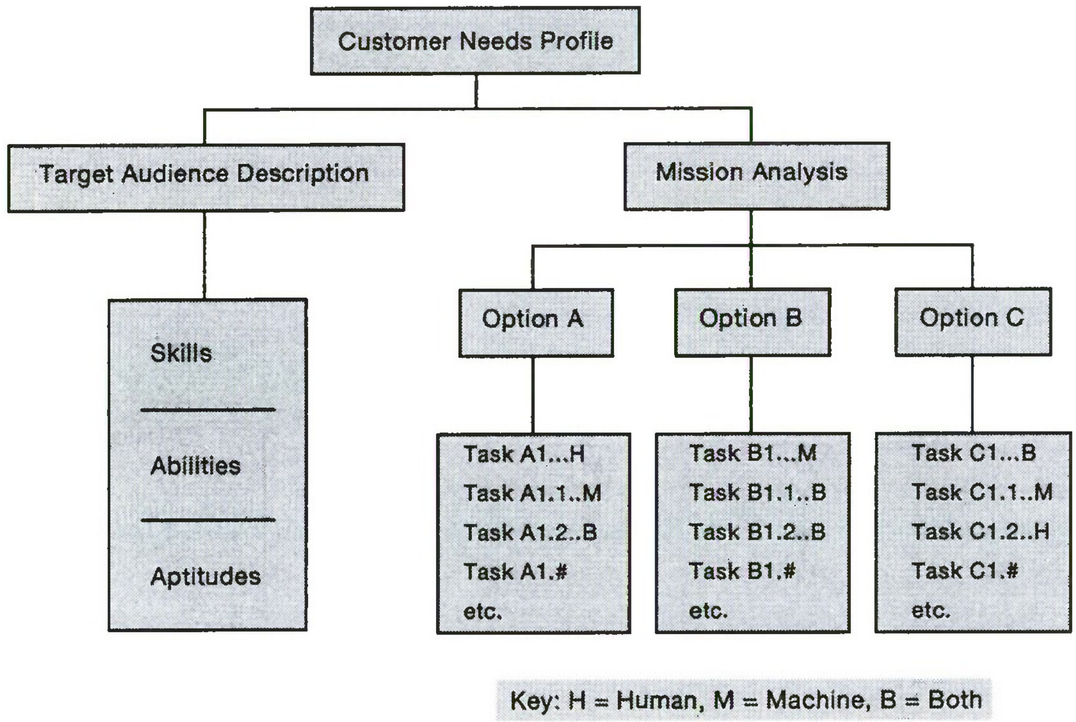


Figure 3.1. The contractor's MANPRINT task.

TECHNOLOGICAL CONSTRAINTS

Technological constraints may include the need to incorporate a particular piece of equipment because the customer has made considerable investments in the item and insists that it be incorporated. The technology may be required to cope with a small proportion of cases, but, since it has to be provided anyway, it may have to cover all cases.

ORGANIZATIONAL CONSTRAINTS

There are often considerable constraints regarding which users within a customer's organization have authority to undertake particular tasks. The organizational constraints within groups of operators can have a profound influence on the allocation process.

POLITICAL AND LEGAL CONSTRAINTS

With changes in legislation and associated commercial responsibility and accountability, there are now many more tasks that it is not possible to allocate to the human component. The increased knowledge of toxic substances, sensitivity to public opinion, and the fear of litigation are causing manufacturers to err very much on the side of caution. Many tasks that could be done "better" by humans must now be assigned to machines.

COMPATIBILITY CONSTRAINTS

Systems are now so complex and costly that, where possible, the reuse of existing designs and the increased use of off-the-shelf systems are the order of the day. It is unusual to start with a blank piece of paper, and so the flexibility available in allocation of functions is immediately limited. In addition, the influences of the "outside system" tasks the user must perform will modify the scope for allocation (see the section "What Is the User's Job?" above).

RESOURCE CONSTRAINTS

The drivers for the allocation process in many modern systems are often the skill levels of personnel available to the customer and the

training time the customer can afford. Training is probably the most significant aspect that has been poorly represented in any of the traditional allocation exercises.

In many of the through-life cost calculations, personnel and training costs can be many times the development and procurement costs. In these instances, the availability of previously trained personnel and training courses are beginning to influence the allocation process on the prime equipment design.

CONCURRENT ENGINEERING

There is a move within industry toward the concept of concurrent engineering. In the past, great efforts have been made to get the requirements correct and adequately documented in such a way that the team responsible for the next phase in the system development life cycle could work from it alone. Concurrent engineering is a recognition that, for the complex systems that constitute modern defense equipment, this approach is no longer possible. The gestation period of modern systems can be up to 15 years and, with the likely technological changes, this can cause a need for modification and consequently reallocation. It is essential that each person involved with the development of the system be aware of the requirements and constraints that apply to others.

ARE FUNCTIONS TOO BIG TO ALLOCATE?

The traditional human factors texts often show a large number of steps that need to be followed to apply ergonomics successfully to a project. These include the following (UK Ministry of Defence, 1989):

- system requirements analysis (or mission analysis);
- functional analysis;
- allocation of functions;
- task synthesis;
- task description;
- task analysis;

  etc.

Jordan (1963) attributed the failure to develop a satisfactory methodology for allocation of functions to the fault of comparing humans with

machines. In the majority of cases, the two have to work in a complementary manner to achieve functional goals successfully. In modern defense systems, the majority of functions need both humans and machines to undertake complementary tasks.

During the development of the MANPRINT program for British Aerospace Dynamics, the search has been for a simple, practical framework that can be used for as many different projects as possible. It has been found that it can be very difficult to explain the difference between a function and a task to engineers who have not been brought up in the human factors community. Similarly, mission analysis and functional analysis blend together to such an extent that considerable time was being spent defining the boundary on a project-by-project basis. The solution that is beginning to be adopted is to remove the term *functional* and to refer only to missions and tasks.

MANPRINT experience suggests that it is nearly always tasks that we allocate when trying to design for the user. Throughout the remainder of this paper, the phrase *allocation of tasks* is used to signify allocation of function/task and function allocation.

THE ALLOCATION PROCESS

There are severe problems in trying to apply Fitts-type lists to modern systems. This is due largely to the vastly increased capabilities of machines. When function allocation came into being as a concept in the early 1950s, the allocation of functions between human and machine was fixed, barring major redesign, very early in the design cycle. Systems were relatively simple, and the process of allocation was fairly obvious. Many of the early lists now look like SOTBOs (statements of the blindingly obvious).

The development of the MANPRINT program has revealed that a different approach to the allocation problem could be beneficial. This approach consists of identifying those tasks for which a human is clearly "best" or is required for legal (or other) reasons, and building a coherent job structure around those tasks. In addition to providing a sensible job content, the determination of an optimal workload is probably the clearest single driver for this allocation process.

WHY DOES THE TRADITIONAL APPROACH CAUSE DIFFICULTIES?

The traditional approach causes difficulties simply because the machine content of the system has changed so much since 1951. As highlighted in the previous section, humans and machines perform tasks in a complementary manner to fulfil functions or sub-mission goals. While these higher-level goals may have an obvious structure, the individual tasks that are necessary to achieve them may not in themselves have that logical structure when taken in isolation. Laughery and Laughery (1987) make the point that "a function can be viewed as a logical unit of behavior of a human or machine component that is necessary to accomplish the mission of the system." When dealing with tasks, the logical units may not be present. Allocation of these tasks to either human or machine purely on the basis of which can do that task best often results in the human's being given those tasks that are too difficult or expensive to automate.

While machines can operate on a task-by-task basis, humans faced with a random selection of tasks that have little logical connection tend not to perform very well. The automation represented by the allocation of tasks to the machine can remove many of the signposts from the user's mental model of the process. This, in turn, leads to the user's inability to provide the resource of last resort, which is often the reason for humans to remain included in the automated system.

WHICH TASKS DO HUMANS DO BETTER THAN MACHINES?

It could be argued that most tasks that can be clearly specified can usually be done better by machine. This is typified by the fact that recently computers have been beating chess grand masters on a regular basis.

There are many development engineers who believe in automating the humans out of the system, since "people are a problem." Bainbridge (1987) notes "the ironies of automation." The first concerns the system designers' perception of the human operator as unreliable and inefficient and better replaced by automation, and the second leaves the operator to do the tasks the system designer cannot think how to automate.

One of the reasons often given for including humans in defense systems is so that they can make decisions. This usually means making decisions with insufficient information since, if all the information were available, the machine would probably reach a correct solution more rapidly. Hitchings (1992), building on the work of Klein, suggests that, in most time-constrained strategic decision making tasks, "satisficing" takes place. This process consists of matching the current problem with one that has been encountered before and activating solutions that appeared to be effective on previous occasions. The user checks that the responses are in line with his or her predictions. If the responses are at variance with expectations, a further matching takes place. This approach to decision making relies on the user's having an understanding of how the system behaves. Indiscriminate automation can mask this essential overview and is one of the prime reasons for the current MANPRINT approach.

The one area where the human still appears to be better and quicker than the machine is in image processing. There are still good reasons for placing humans in such vulnerable situations as military aircraft. For example, human beings are very good at detecting that something seems odd. They may not know what is odd or why, but the very recognition of an inconsistency could be vital in a hostile environment.

BUILDING JOBS

It is becoming more important that the user's mental model of the system be established early in the design process. If the unique strengths of the human operator are to be capitalized upon, then the way the operator perceives the system must be understood. The jobs (positions, in US parlance) that the operator must perform need to be designed to ensure that the way the operator views the system results in the performance of actions the system designer would have intended. There are two points here: first, the user may view the system in a different way from the system designer; and, second, the user is there to cope with situations the system designer could not predict.

In many cases, it is better to give to humans tasks that would have been done better by machine, but without which they would not have a complete enough picture of the world to perform those tasks that *are* their remit. Without constant exposure to the "big picture," it is doubtful if many of the potential users of modern defense systems will have

sufficient understanding of the system's inner workings to be able to intervene successfully in case of either an equipment malfunction or changes in the environment.

The challenge is to discover how the users visualize the system and ensure that any action they may take is not at variance with the intent of the system developers because of their different perceptions of the system. If there is a conflict, it is salutary to remember that the system designer may only live with the system for 5 to 10 years, while the user has it for 25!

WORKLOAD AS THE ALLOCATION METRIC

The foregoing was theory. How do we accomplish allocation of tasks in practice? First, we assign tasks according to a set of SOTBOs. That is, we assign those tasks that require the cube roots of a five-digit number to be calculated within 10 msecs to the machine, and assign the launching of nuclear ballistic missiles to humans.

Second, we assess what understanding the human needs of the total system in order to perform his or her tasks correctly and efficiently. From this, we assess which other tasks the operator could be involved in that would help to develop and reinforce an adequate mental model of the system. In other words, we assign tasks to ensure that the action the user performs corresponds sufficiently with the system developers' models of the system so that a satisfactory outcome is achieved.

Third, the workload on the user must be assessed. It is this step that should determine which tasks are given to the human component, and it is also this step that should be the arbiter of which tasks can or should be the subject of automatic reallocation. (If ease of automation is used to determine allocation of tasks, situations arise such as that found on the civil airliner flight deck. Automation of the boring long-haul portions of the route are easiest and have been incorporated in the majority of modern aircraft. However, this automation takes place when the air crew workload is negligible anyway. A change of runway on the final approach or a change to a holding pattern requires the pilot to become a data-entry operative instead of looking out of the windscreen in what is clearly a confused situation.)

As stated earlier, much of the work on allocation has been with very constrained populations and working environments: fast jets, air traffic control, and nuclear power plants. In most cases, the target audience is

highly screened and uniform. The work patterns are constrained and of fixed duration. These circumstances are rare for large numbers of military systems that have to be developed under the MANPRINT program. The variability within most user groups could cause optimal allocation to change from one end to the other. It can often be necessary to design systems that will be issued to groups ranging from Armed Forces Qualification Test categories Cat I to Cat IV.

In addition, when dealing with systems where time on duty can greatly exceed that seen in cockpits, the change in user performance with fatigue will also change the optimal allocation for the beginning and end of a watch period.

The MANPRINT activities that have been undertaken indicate that it is this optimizing of the workload that should be the driver to the allocation of function within any system. What are required are simple workload prediction tools that can be used early and quickly. Many of the tools that do exist have been designed for very demanding situations such as the cockpit of a modern fast jet. The precision being sought for these tools is neither necessary nor appropriate for the majority of allocation activities because of the variability that is to be expected in the performance of the user populations.

ADAPTIVE AND DYNAMIC ALLOCATION

Both dynamic and adaptive allocation systems have been proposed to avoid the problem of the system designers' having to make the decisions on allocation between human and machine. Rouse (1981) considered some of the interesting aspects of dynamic allocation of tasks, particularly the aspect of who is in control. Does the human delegate procedural aspects of the job to the machine, or does the machine monitor the human's activities and assume control of those facets that are not being attended to adequately?

The dynamic allocation technique currently used most commonly within defense industries is that of providing default settings. Where tasks can be performed either by human or machine, the human operator is given the opportunity to override the default condition if the operator feels she or he has access to better information than the machine. While this is not a very adventurous approach, it is pragmatic and, most importantly, it does meet with the approval of the users.

Dynamic allocation will carry with it a number of quality and safety problems. In particular, there is likely to be considerable discussion with the Ordnance Board on how to validate the safety of any system that changes its mode of control. Audits both for quality and for Failure Mode Effects & Criticality Analysis (FMECA) will need very careful consideration and, again, validation. Even then, meeting the standards required by the Ordnance Board may be very difficult.

THE WAY FORWARD

Developing the British Aerospace MANPRINT program has revealed that the two crucial formal activities are the preparation of the Manufacturer's MANPRINT Management Plan (M^3P) and the creation (and maintenance) of the Concerns Register. The former ensures that thought has been given to both the management and technical aspects of designing for the user. The second provides a formal record of the problems encountered, solution paths, and final decisions regarding the way the problem should be overcome. The Concerns Register has proved invaluable on a number of projects, since it contains information on the underlying assumptions that have been made when selecting a particular approach. Many of the MANPRINT concerns in modern defense systems are related to the allocation of tasks between human and machine. For this reason, a short-term aim has been to modify the Concerns Register to ensure that it can capture the factors and the thinking that goes into allocating tasks to either human or machine. It is also important that the record of allocation be linked to the best possible description of the users in question.

A long-term aim is to produce a task database that carries information on learning difficulty, retention times, etc., with links to specific user populations. The relative susceptibility of the tasks to fatigue effects and the human resources needed are also being included in the database. Figure 3.2 shows where the task database fits into the current development of a MANPRINT manpower, personnel, and training trade-off tool. This project is the subject of a research study within British Aerospace's Dynamics Division.

Based on tasks analyses of some of the company's systems, a number of common tasks have been identified. For each of these tasks, efforts are being made to establish how performance on these tasks will vary with different user populations. Because of the potential enormity of

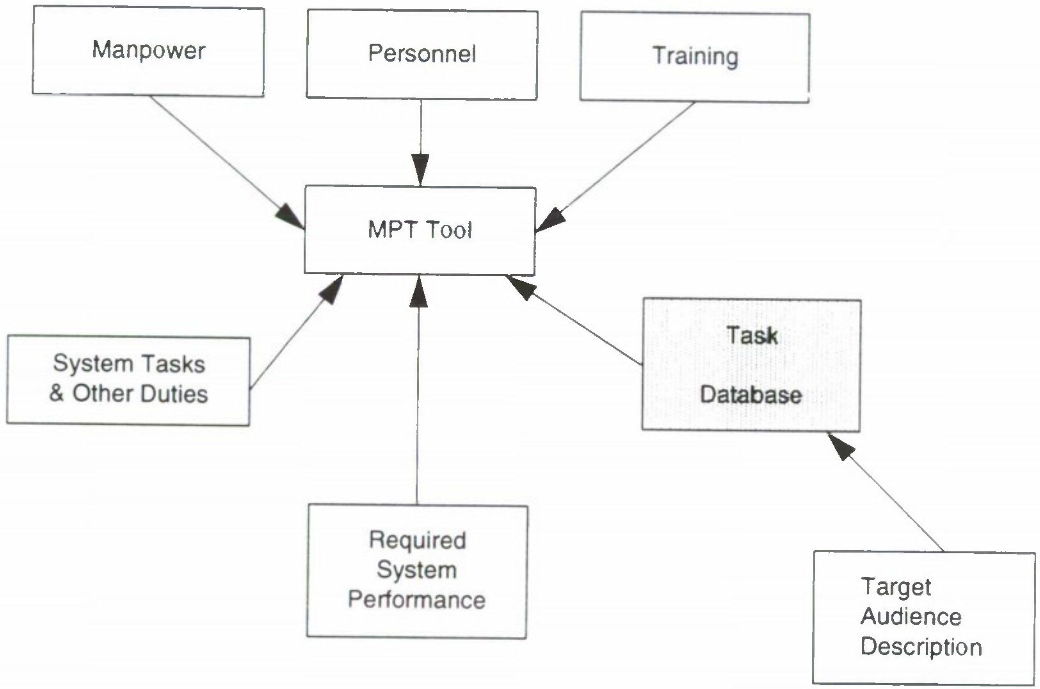


Figure 3.2. The MANPRINT task database and how it fits into the development of a MANPRINT manpower, personnel, and training (MPT) trade-off tool.

this undertaking, we are confining our task base to those few tasks that are common to a number of our systems. By constraining the scope of the database, it is hoped that it will be possible to build directly from project work and that an assessment of the approach can be carried out without committing large amounts of funds.

CONCLUSIONS

Allocation of functions (tasks) in complex weapon systems traditionally is done poorly and is often done for the wrong reasons. It is important to recognize the uscrs' characteristics and capabilities in the allocation process.

It is not sufficient merely to assess suitability of tasks for operator or machine implementation. The operator needs to retain sufficient understanding of the system to perform satisfactorily and predictably, while not being loaded beyond his or her capabilities. The British Aerospace MANPRINT developments indicate some of the practical solutions to task allocation and some pointers for futurc attention.

REFERENCES

Bainbridge, L. (1987). The ironies of automation. In J. Rasmussen, K. Duncan, & J. Leplat (Eds.), *New technology and human error* (pp. 271-283). London: Wiley.

Booher, H. R. (Ed.). (1990). *MANPRINT: An approach to systems integration.* New York: Van Nostrand Reinhold.

Hitchings, D. K. (1992). *Putting systems to work.* Chichester, England: Wiley.

Jordan, N. (1963). Allocation of functions between man and machines in automated systems. *Journal of Applied Psychology, 47,* 161-165.

Laughery, K. R., & Laughery, K. R., Jr. (1987). Analytical techniques for function analysis. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 329-354). New York: Wiley.

Rouse, W. B. (1981). Human-computer interaction in the control of dynamic systems. *Computing Surveys, 13*(1), 71-99.

Stammers, R. B., & Hallam, J. (1985). Task allocation and balancing of task demands in multi-man-machine systems—some case studies. *Applied Ergonomics, 16*(4), 251-257.

UK Ministry of Defence. (1989). *Human factors for designers of equipment: Systems* (DEF STAN 00-25 [Part 12]). Glasgow: Ministry of Defence, Directorate of Standarization.

4

HUMAN FUNCTIONS AND SYSTEM FUNCTIONS[1]

D. Beevis

Typically, function analyses concentrate on the functions necessary to meet system requirements; they seldom address all the functions performed by humans. Crew functions such as supervision, monitoring, direction, consultation, and training are not included in function analyses or in the allocation of functions. The reason is that such human functions are assumed or are identified only once function allocation decisions have been made. Yet the performance of these human functions can have a major influence on the design and performance of manned systems. As one example, a major human factors engineering contribution to the CP-140 maritime patrol aircraft was the crew compartment layout. The layout was predicated on the need to produce an effective crew compartment that facilitated crew activities such as supervision, task off-loading, assistance, and training. Yet none of the function analyses produced for the CP-140 systems included those human functions. The crew compartment layout was established in parallel with the systems engineering efforts that established the functional analyses. The approach to analyzing the compartment requirements and the human and system functions is described. It is concluded that analysts must consider human functions as part of their function allocation decisions.

INTRODUCTION

Despite the human focus of ergonomics and human factors, most approaches to function allocation treat the human as a mechanism, the abilities of which are comparable to those of a machine. A few approaches have tried to widen the scope of the function allocation analysis to include specific human needs. Fitts (1962) raised the question of job satisfaction. Clegg, Ravden, Corbett, and Johnson (1989) argued that function allocation should include human health and safety considerations in the decision. Drury (1994) expanded on this approach to include the following factors in the function allocation decision:

- System effectiveness
  errors/reliability
  speed
  maintainability
  weight/size where limiting
- System efficiency
  initial cost
  running cost
  disposal cost
- Human well-being
  safety
  health
  satisfaction

None of these approaches, however, takes into account the requirements of the human resources in a system for interaction, collaboration, monitoring, supervision, training, etc. Function analyses concentrate on the functions necessary to meet system requirements independently of the means of implementation (Beevis, 1992). Human resource functions are not included in the function analyses of a system; they are assumed or are identified once function allocation decisions have been made. Reviews of the function analyses of five major military systems (aircraft, ship systems, communication system) selected at random did not identify any human resource functions such as interaction, collaboration, monitoring, or supervision (Beevis, 1987).

This neglect of human resource functions is part of a general pattern.

As Edwards (1993) noted, "the balance of ergonomics activities does far less than justice to the issues of inter-personal relationships in the design and management of systems." Yet the performance of the human resource functions can have a major influence on the design and effectiveness of manned systems. This is reflected in the increasing emphasis placed on crew performance by developments such as the adoption of crew resources management in aircraft operations (Alkov, 1994; Wiener, Kanki, & Helmreich, 1993). The following case study is offered to show that human resource functions are important determinants of system design, and that the importance of function allocation lies in its contribution to a larger cycle of iterative analyses.

SYSTEMS ANALYSIS FOR THE CP-140 AURORA AIRCRAFT

THE CP-140 AURORA PROJECT

The Canadian Forces (CF) CP-140 Aurora Maritime Patrol Aircraft (MPA) was developed in the early 1970s to replace the CP-121 Argus, dating from the late 1950s. The Argus used a tactical crew of nine organized on the traditional basis of assigning an operator to each major item of equipment (radar, passive sonar, active sonar, navigation, etc.). The functional requirement for the CP-140 required "a tactical crew area aft of the flight station which shall include accommodations with necessary equipment for sensor station operators, tactical navigator, and combined routine navigator and communications operator, as directed by the Department" (Canadian Armed Forces, 1973). Thus, the functional specification for the aircraft implied a reduced crew complement and defined some operator roles.

Proposals received from industry, however, included four different crew concepts, identified as numbers 1 through 4 in Table 4.1. The overall level of mechanization was similar for all four proposals. Thus, the allocation of functions between human and machine did not account for much variance in the proposals. It was the allocation of functions to individual crew members that accounted for most of the differences. The bidders had established their proposed crew complements by assigning system functions to the individual crew members based on considerations such as the operator's workload and need for information. The

Table 4.1. Assignment of functions to operators in four different proposals for a maritime patrol aircraft

SUBSYSTEM	OPERATOR ASSIGNED SUBSYSTEM (In Proposal 1, 2, 3, or 4)									
	Tactical Navigator	Routine Navigator	Radar Operator/ Navigator	Radar Operator	Routine Navigator/ Comms Operator	Comms. Operator	Acoustic Sensor Operator 1	Acoustic Sensor Operator 2	Non-acoustic Sensor Operator 1	Non-acoustic Sensor Operator 2
Tactical Plot	1, 2, 3, 4									
Navigation Systems		1, 2	3		4					
Communication Systems					4	1, 2, 3				
Radar	1, 4		3	2					1, 4	
Interrogation Friend or Foe/ Electronic Support Measures			3	2					1	3, 4
Electronic Countermeasures									2, 3	4
Magnetic Anomaly Detection									1, 3, 4	
Forward Looking Infrared	1, 2, 4	2							3, 4	1
Low Light Level TV	1, 2, 4	2							3, 4	1
Infrared Line Scan	1, 2, 4	2							3, 4	1, 2 4
Sideways Looking Airborne Radar	1, 2, 4								3, 4	1, 2, 4
Cameras	1, 2, 3, 4									
Acoustics - Active							1, 2, 3, 4	1, 2, 3, 4		
Acoustics - Passive							1, 2, 3, 4	1, 2, 3, 4		
Bathy - Thermograph		2					4			3

human factors analysts had completed the iterative cycle shown in Figure 4.1 from performance prediction (stage 5) back to function allocation (stage 3) to review the implications of function allocations for operator tasks and operator workload.

The analyses had been conducted at a fairly gross level. The bidders' analysis appeared to have been made on the basis of "second-level" function analyses of the form "conduct radar search," or "operate passive acoustic sensors." This was a deviation from the recommendation that function allocation be based on system functions analyzed to the third or fourth level (Beevis, 1992). In using higher-level analyses, two of the bidders had the benefit of information from existing maritime patrol aircraft, so they were able to base their designs on existing systems, a practice noted by Rouse and Cody (1986).

Two bidders did not have such ad hoc information available from existing products but were believed to have expertise in MPA design available to them from subcontractors.

As can be seen from Table 4.1, there was general agreement in the proposals about the allocation of functions for tactical navigation (TACNAV) and the operation of the acoustics subsystems (ASOs 1 and 2). The major differences in allocation of functions arose in the operation of the radar and navigation systems and the employment of other nonacoustic sensors. These differences resulted in proposals for tactical crew complements of six or seven operators, depending on equipment fit. As might be expected, the differences in function allocation and crew composition resulted in quite different tactical crew compartment layouts. Detailed reviews of the proposed crew compartments by human factors specialists at the Defence and Civil Institute of Environmental Medicine (DCIEM) identified several areas in which the proposed functions and crew complements would not meet CF operational requirements in the most effective manner (Patterson & Beevis, 1973). As a result, DCIEM was tasked by the project management office to develop a CF-preferred tactical crew compartment concept.

DEVELOPMENT OF THE CREW AND CREW COMPARTMENT CONCEPTS

To develop the crew compartment concept, the human factors specialists at DCIEM reviewed the information that was required for workplace

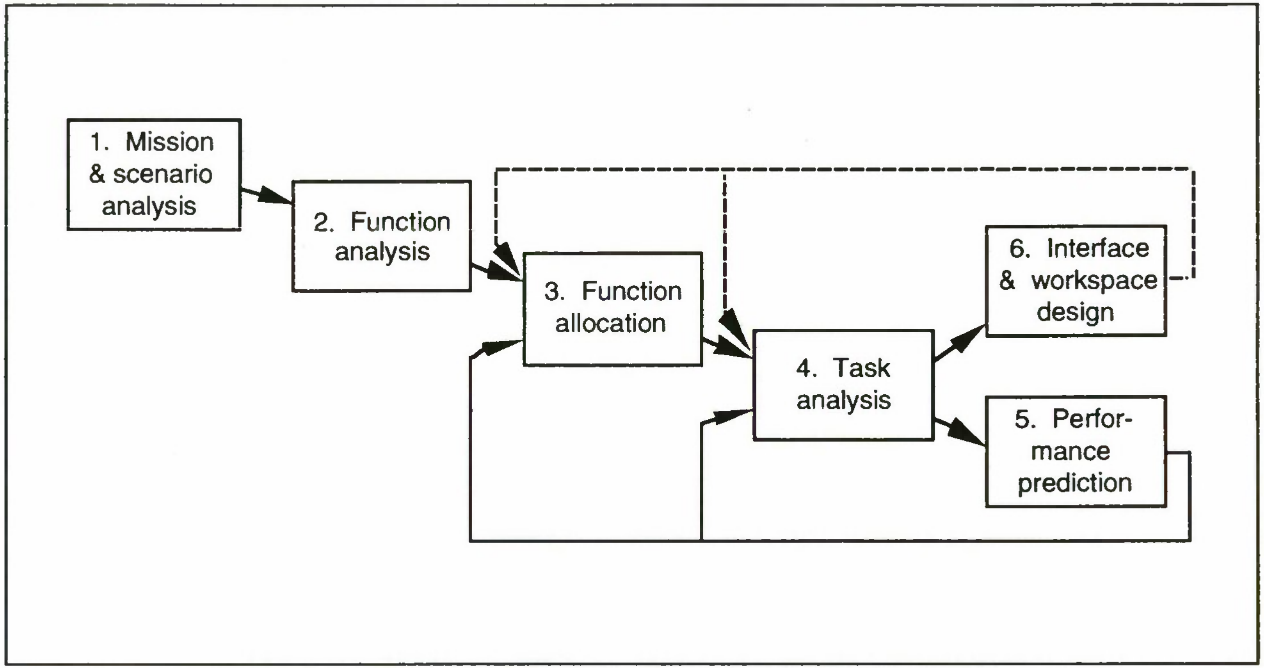


Figure 4.1. Feedback in the human factors engineering analysis process.

layout (Morgan, Cook, Chapanis, & Lund, 1963), including:

- the system mission profiles;
- specific tasks the operators would perform;
- relative importance, duration, and frequency of the tasks;
- information inputs to the operators;
- outputs from the operators;
- equipment committed to the design;
- anticipated environmental conditions (aircraft movement etc.).

Thus, DCIEM involvement in the analysis of interface and workspace design issues (stage 6 in Figure 4.1) resulted in reexamination of function allocation decisions and operator task analysis (stages 3 and 4 in Figure 4.1). A variety of crew complements and operator roles was studied, including:

- dedicated radar operator;
- dedicated routine navigator;
- dedicated communications operator;
- combination of routine navigator and communications operator (NAVCOM);
- combination of navigator and radar operator (RADNAV).

Sources of information used for this work were observations of the operations in the (then) current CP-107 Argus and observations of the Royal Air Force (RAF) Nimrod and US Navy (USN) P-3C Orion MPA. System mission, function and task analyses, and time lines (Beevis, 1992) for the proposed CP-140 aircraft were also developed and analyzed. This information was used to identify constraints on the allocation of operator roles and functions and to review possible function allocations.

Based on experience with the CP-107 Argus, it was concluded that a tactical navigator (TACNAV) similar to the Argus tactical coordinator (TACCO) would be able to handle all crew coordination duties, particularly given the integration of sensor and display systems available in the (then) new generation of antisubmarine warfare equipment. The RAF concept of a walking tactical crew coordinator was judged to be a function of the Nimrod crew compartment layout and not required for the CP-140. A review of USN experience with the combined navigator/communicator (NAVCOM) position in the P-3C aircraft suggested that such a role or position was feasible for the CP-140. Although the RADNAV role was justified by one bidder as involving minimum

change to existing CF specialties and training, the question of retraining for the proposed roles was not considered in detail by DCIEM.

The question of crew structure had to be resolved early enough to permit the development of the necessary training program, however. Therefore, operational units produced position papers on training, crew complement, and the two most contentious function allocations: NAVCOM and RADNAV. Two position papers produced conflicting conclusions.

One argued for the RADNAV role, on the basis of the following:

- training requirements;
- "remoteness" of the communicator from tactical operations;
- the obvious relationship of radar to the navigation function;
- emergency situations that demanded immediate response by the navigator for position information and by the communicator for distress calls;
- ability of a RADNAV to assist the TACNAV in high workload situations;
- the workload imposed on the communicator in the event of tactical computer failure.

The other position paper noted that the P-3C NAVCOM position was "not without its problems" but argued that the disadvantages of the RADNAV role outweighed those of the NAVCOM. The principal disadvantages were thought to be:

- the high workload associated with the use of radar and electronic support measures (ESM) systems in tactical situations;
- the need to avoid distractions to this work, such as might be caused by navigation system updates;
- the need to rotate different operators through the function in a tactical situation to avoid vigilance decrements.

Overall, the major source of disagreement between the two position papers concerned the estimate of operator workload at different times in the aircraft mission.

The position papers that addressed the question of crew development and training suggested that either of the crew concepts could be trained. The more difficult issue was the question of tactical crew makeup, in

terms of officers and noncommissioned officers (NCOs). It was this latter consideration that decided the argument in favor of a NAVCOM role rather than RADNAV. Because encrypted communications must be authorized by an officer, the communications function had to be performed by an officer. Both tactical navigation and routine navigation had to be performed by officer classifications as well, whereas radar operation in the Argus was performed by NCOs who were rotated through the position during a mission. A crew that included a RADNAV position would have required one officer for that position as well as one each for the TACNAV and communicator positions. In contrast, a crew with a TACNAV and NAVCOM would require only two officers. Thus, the allocation of functions to different members of the crew was decided on the basis of rank and trade specialty considerations.

INFLUENCE OF WORKPLACE DESIGN ON FUNCTION ALLOCATION

In parallel with the review of crew functions, the requirements for a tactical crew compartment "arranged to conform to the best human engineering practices" (Canadian Armed Forces, 1973) were analyzed. Observations of RAF Nimrod operations highlighted the importance of crew coordination. The RAF used an airborne equipment operator (AEO) as a walking tactical coordinator who moved from crew station to crew station coordinating crew operations, instructing, and resolving conflicts and ambiguities. Observations made aboard a USN P-3C aircraft when an unforeseen event occurred during the mission confirmed the importance of crew coordination, particularly for consultation and problem solving. It was noted that the compartment of the P3-C had been arranged to minimize unnecessary crew interaction and to require such interaction through either the mission computer or the intercom.

Analytically, the issue became one of identifying the advantages of and requirements for an integrated tactical crew compartment. It was argued that, in a well-planned compartment, emphasis is placed on close physical proximity and face-to-face communications. In this context, it was noted that the claim by one bidder that two crew members would be able to load-share was not supported by the design of the compartment, which separated them physically.

The following were seen to be the potential advantages of an integrated layout (Patterson & Beevis, 1973):

i) It encourages a coordinated team effort:
   - should one operator be overloaded, another crew member can assist, provided their stations are adjacent;
   - other crew members can be consulted in cases of ambiguity or conflicting information.

ii) Senior crew members can more easily monitor the performance of junior crew members.

iii) Crew rotation is facilitated:
   - crew members can maintain an overview of the tasks at adjacent consoles, to which they may rotate;
   - in-flight training is facilitated, since face-to-face communication is possible, leaving the intercom free for operational information;
   - reversionary modes of operation are possible, in the event of equipment failure;
   - crew interaction maintains attention during long periods of monitoring.

These advantages implied the following human-subsystem functions:

- coordination;
- consultation;
- resolution of ambiguity;
- crew performance monitoring;
- maintenance of awareness of system state;
- training;
- reversionary mode operation, and;
- maintenance of alertness.

None of the function analyses provided by the bidders or prepared by the Canadian Department of Defence (DND) included these functions. Task analyses produced by contractors and the DND following the review of the proposals provided more detail related to the operation of the aircraft equipment but did not include tasks reflecting human subsystem functions. "Function allocation" itself was not a work item in the human factors engineering project plan provided by the two contractors selected for the subsequent project definition studies. Presumably, they considered the function allocation analysis to be complete. Yet the

human subsystem functions listed above had a major influence on the development of the concept of the crew compartment, as well as implications for operator workload and equipment design. The features of an integrated crew compartment were incorporated in a set of design requirements (Patterson & Beevis, 1973):

- the tactical navigation station should be adjacent to the routine navigation station;
- the acoustic sensor stations should be adjacent;
- the nonacoustic sensor stations should be adjacent;
- the acoustic sensor stations and the nonacoustic sensor stations need not be adjacent;
- both the acoustic sensor stations and the nonacoustic sensor stations should be as close as possible to the tactical-navigation and routine navigation stations.

These requirements were embodied in two crew compartment designs for the CP-140 that were produced as simple mock-ups. The concept was developed further through extensive analysis and mock-up trials by DCIEM using operators with experience in a variety of MPA. The results of those analyses were then passed to the two contractors selected and funded for project definition.

Late in the project, the value of the integrated crew compartment was questioned, compared to the lesser cost of adopting the design of an existing aircraft. The question was interpreted in terms of the contribution to system effectiveness of the integrated compartment design. As noted above, the function, task, and workload analyses conducted by the contractors performing system definition studies had not addressed the functions that were facilitated by the crew compartment layout. Fortunately, questionnaire surveys to identify actual operator roles, duties, functions, and tasks in USN P-3C and S-3A aircraft did identify tasks related to coordination and supervision (Helm, 1972, 1975).

To address the contribution of the integrated crew compartment concept, the P-3C function and task descriptions were compared with the equipment fit and tasks anticipated for the CP-140. Sufficient commonality was found at the system level to justify applying the task descriptions for the P-3C to the proposed CP-140. Of 418 tasks for the TACCO identified in the USN P-3C survey (Helm, 1972), 106 were judged to be facilitated by the adoption of the integrated compartment design (Beevis, 1975). Examples of those tasks are shown in Table 4.2.

Table 4.2. Examples of tasks performed by P-3C tactical coordinator (TACCO) that involved coordination, supervision, and crew monitoring

Position: Tactical Coordination (TACCO), Role: Coordinator
Coordinate information from radar with other system sensors using the computer or console display
Coordinate information from magnetic anomaly detection (MAD) with other system sensors using the computer or console display
Communicate with the sensor operators concerning analysis, classification, and evaluation of either acoustic or electronic contacts
Evaluate signature characteristics of contact on sonar graphical recorders
Evaluate and compare the classification and analysis of acoustic/nonacoustic sensor contacts with the sensor operators
Direct sensor operators on appropriate watch rotations, monitoring cycles, and work-rest cycles during the flight
Direct crew stations concerning all tactical actions to be executed by the crew or by individual stations
Monitor and supervise voice communications and other related duties of navigation/communications operator
Monitor status of navigation and communications equipment
Insure that the radar operator enters all contacts into the system

Source: From Helm (1972).

On the basis of that analysis, which related operator functions and tasks to the design of the workspace, the CF proceeded with the development of the integrated crew compartment for the CP-140.

DISCUSSION

One obvious question is whether the effort devoted to the human resource functions in the CP-140 was justified. Crew functions and the crew compartment design were not tested in the operational evaluation prior to phasing the aircraft into service (Maritime Air Group, 1980). Once the aircraft was in service, however, unpublished surveys of aircrew identified few major problems. In general, reports about the crew functions and workload have confirmed predictions made during the concept development. In certain missions, workload at the NAVCOM station is reported to be very high for long periods. It should be noted that those missions were not included in the original requirements for the Aurora and were not included in the mission, function, task, or workload analyses. As for the resulting crew compartment design, there have been many favorable comments from aircrew. A third-party review of the tactical crew compartments of current NATO MPA judged the Aurora as "perhaps the best integrated multi-crew/avionics system [in an MPA] flying anywhere in the world" (Lovesey, 1988.)

Another question is whether the issues arising during the Aurora project were typical. The CP-140 was not the only DCIEM project in which human subsystem functions became important determinants of function allocation and crew station layout. Questions of collaboration, supervision, and monitoring have arisen in several projects, including the design of ship's bridges (Beevis, 1978) and the development of ship's machinery control consoles (Gorrell & Beevis, 1985). More recently, in the CF Light Helicopter project, one issue was that the equipment fit might require a change in the crew concept from that of the existing CH-136 Kiowa, in which the pilot is the crew commander and is assisted by an NCO. An investigation using knowledge elicitation techniques among CH-136 aircrew identified four constructs that distinguished different crew concepts: structure and composition, knowledge, workload, and effectiveness (Poisson, 1989). Measures of effectiveness used in a subsequent computer simulation of the two most promising crew configurations (pilot/commander plus observer, and pilot plus mission commander) showed differences between the two

configurations. Those differences were due to extensive differences in communication between the crew configurations that affected operator workload (Hendy, Kobierski, & Youngson, 1992). Thus, the allocation to different crew members of functions involving supervision, coordination, consultation, etc., was again shown to affect workload, system design, and system effectiveness.

On the more general issue of function allocation, the CP-140 case study shows clearly that the process of function allocation does not stand on its own, but that it is one of an interrelated series of analyses that must be reiterated. Initial solutions may be obtained on the basis of function decompositions to the second level only. The solutions derived from those initial analyses did not converge to one concept, however, but differed quite widely in allocation of functions to different crew members, in estimates of workload, and in crew complement. Further iterations were necessary to converge to one preferred crew concept. Various human factors engineering issues were addressed not in the structured, sequential way described in human factors texts, but in a very fluid manner. This accords with more recent observations that the application of human factors in design involves a continually changing problem environment (Burns & Vincente, 1994). Rather than being treated as sequential steps, the stages of human factors engineering analysis shown in the figure in the Executive Summary can be treated as work items that must be completed (Burns & Vincente, 1994).

In this context, it is hard to agree with criticisms that allocation of function generates few particular results (Fuld, 1993). It may be that large tabular comparisons of human and machine capabilities on a third-level, function-by-function basis do not add value to systems analysis efforts, but that is not the issue addressed here. The purpose of this paper is to argue that function allocation goes well beyond the simple concept of deciding whether a function should be performed by a machine or a human.

Some may consider that the issues raised are not part of function allocation as normally practiced. Those issues were raised, however, to illustrate that the allocation of functions among members of a crew is important and involves functions that are uniquely human. While the allocation of functions between humans and machines may not be contentious, the allocation of functions among different members of a crew may be. That some functions in CP-140 were allocated on the basis of rank and specialty demonstrates a potential link between human factors

engineering and manning, personnel, and training issues that is important for liveware (or human systems) integration (NATO Defence Research Group, 1993).

CONCLUSIONS

On the basis of the foregoing case study, we can draw several conclusions.

First, although the actual design process is unstructured rather than sequential, human factors engineering analysis stages such as those identified in the NATO review of human engineering analysis techniques (Beevis, 1992) or US *MIL-H-46855B* (US Dept. of Defense, 1979) can be used as milestones in that process. Within the human factors engineering process, function allocation contributes to the overall development of a system concept through its support to an iterative cycle of analyses. The initial cycle of human factors engineering analyses can be completed using second-level systems functions if information is available from existing systems, but further iteration is probably required to converge to a solution. Analysts must consider human resource functions such as collaboration, monitoring, supervision, and training as part of their function allocation decisions. Personnel rank, specialty, and training may be important determinants of function allocation decisions and may provide a link for integrating manpower, personnel, training, and human factors engineering considerations in system development.

REFERENCES

Alkov, R. (1994, April). Enhancing safety with crew coordination training. *Ergonomics in Design, 2*, 13-18.

Beevis, D. (1975). *Advantages of an integrated tactical crew compartment in the LRPA* (Technical Memo to Directorate of Maritime Air). North York, Ontario: Defence and Civil Institute for Environmental Medicine.

Beevis, D. (1978). *Human engineering considerations in the design of the bridge for the Canadian Patrol Frigate (CPF): Preliminary observations and conclusions* (Technical Report 78X13). North York, Ontario: Defence and Civil Institute for Environmental Medicine. (Restricted)

Beevis, D. (1987). Experience in the integration of human engineering effort with avionics systems development. In *The design, development and testing of complex avionics systems* (AGARD CP 417, pp. 27-1–27-9). Neuilly-sur-Seine, France: NATO Advisory Group for Aerospace Research and Development.

Beevis, D. (Ed.). (1992). *Analysis techniques for man-machine systems design* (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

Burns, C. M., & Vincente, K. J. (1994). *Human factors design guidance: Matching the advice to designers' questions* (Final Contract Report for the Defence and Civil Institute for Environmental Medicine). Toronto: University of Toronto, Cognitive Engineering Laboratory.

Canadian Armed Forces. (1973). *Air specification 15-14: Long range patrol aircraft* (Issue 4). Ottawa: Director General Aerospace Engineering and Maintenance.

Clegg, C., Ravden, S., Corbett, M., & Johnson, G. (1989). Allocating functions in computer integrated manufacturing: A review and a new method. *Behaviour and Information Technology, 8*(3), 175-190.

Drury, C. G. (1994). Function allocation in manufacturing. In S. A. Robertson (Ed.), *Contemporary ergonomics: Proceedings of the Ergonomics Society's 1994 Annual Conference* (pp. 2-16). London: Taylor and Francis.

Edwards, E. (1993). What is in a name? *The Ergonomist—The Newsletter of the Ergonomics Society, 275,* 1, 4.

Fitts, P. M. (1962, January). Functions of man in complex systems. *Aerospace Engineering, 21,* 34-39.

Fuld, R. B. (1993, January). The fiction of function allocation. *Ergonomics in Design, 1,* 20-24.

Gorrell, E. L., & Beevis, D. (1985). *A study of the human engineering design requirements for naval ship machinery control consoles.* Unpublished report. North York, Ontario: Defence and Civil Institute for Environmental Medicine.

Helm, W. R. (1972). *Naval flight officer function analysis: Vol. 1. P-3C Tactical Coordinator (TACCO).* Pensacola, FL: Naval Aerospace Medical Research Laboratory.

Helm. W. R. (1975). The function description inventory as a human

factors tool in evaluating system effectiveness in operational environments. In *Proceedings of the Human Factors Society 19th Annual Meeting* (pp. 206-208). San Diego: Human Factors Society.

Hendy, K. C., Kobierski, R. D., & Youngson, G. A. (1992). The integration of human factors engineering analyses with manpower, personnel and training studies. In *Proceedings of the NATO DRG Panel-8 Workshop on Liveware Integration Needs* (AC/243 [Panel 8] TP/5). Brussels: NATO Defence Research Group.

Lovesey, E. J. (1988). *Visit to the Defence and Civil Institute for Environmental Medicine, Ontario and Canadian Forces Base, Greenwood, Nova Scotia* (Report D/RAE/MM5/23/5/1/34). Farnborough, UK: Royal Aircraft Establishment.

Maritime Air Group. (1980). *Project plan for OPVAL/A1000: The operational evaluation of the CP-140 Aurora.* Halifax, Nova Scotia: Maritime Air Group.

Morgan, C. T., Cook, J. S., Chapanis, A., & Lund, M. W. (1963). *Human engineering guide to equipment design.* New York: McGraw-Hill.

NATO Defence Research Group. (1993). *Workshop on Liveware Integration Needs* (Technical Proceedings, NATO DRG AC/243 [Panel 8] TP/5). Brussels: NATO Defence Research Group.

Patterson, R. D., & Beevis, D. (1973). *TCA Layout in the LRPA: Interim Report* (DCIEM Operational Report No. 73-R-949). North York, Ontario: Defence and Civil Institute for Environmental Medicine.

Poisson, R. (1989). *CH 136 crewing preferences* (Technical Memorandum 3753A-P51C5[HFD]). North York, Ontario: Defence and Civil Institute for Environmental Medicine.

Rouse, W. B., & Cody, W. J. (1986). Function allocation in manned system design. *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics,* 1600-1606.

US Department of Defense. (1979). *Human engineering requirements for military systems, equipment and facilities* (MIL-H-46855B). Washington, DC: Department of Defense.

Wiener, E. L., Kanki, B. G., & Helmreich, R. L. (Eds.). (1993). *Cockpit resource management.* San Diego: Academic Press.

5

FUNCTION ALLOCATION AND AUTOMATION IMPLEMENTATION IN THE US AIR FORCE

J. W. McDaniel

Advances in digital electronics and software are causing revolutionary changes in the crew system. Offered an unprecedented amount of information, pilots have demanded more "situation awareness," only to complain of workload problems. Many believe effective function allocation has the greatest potential for solving these types of problems. This paper discusses the issues and special problems associated with function allocation and its importance to the design of complex military systems. It also reviews function allocation from the perspective of different levels, from top-level management in the US Department of Defense (DoD) down to the human factors engineers that support the program and the laboratory scientists and engineers that develop new design aids. Modern crew system design is a complex issue that should not be addressed piecemeal but requires an integrated process and design support system to help manage the process.

INTRODUCTION

After aerodynamic and propulsion technologies matured in the late 1960s and early 1970s, the burgeoning technologies of digital electronics and software began to dominate aircraft design and are causing revolutionary changes in the crew system. Electronic technology can now offer pilots an unprecedented amount of information and control in the cockpit. Pilots have responded by expressing a need for more "situation awareness." The avionics (aviation electronics) engineers eagerly rushed to meet this need with a host of new capabilities so vast that pilots

began to complain of workload problems. At the same time, the thoroughly investigated crashes of civil transports have increasingly pointed to sloppy implementation of automation as a cause. Sparaco (1994) identified poor human factors engineering as the cause of a crash of an A320 commercial transport in 1992, saying, "Complex human factor issues that contributed to the accident underscore the need to more fully understand the implications of man/machine interface as increasingly advanced technologies are used on civil transport aircraft."

Sounding the alarm, the editorial in the same January 3, 1994, issue of *Aviation Week & Space Technology* said, "Human error is the cause of the vast majority of civil aircraft accidents.... Getting the man-machine interface right is becoming more challenging as aircraft designers decide how many *functions* to automate and how to keep the pilot in the loop." The Federal Aviation Administration's chief human factors engineer, Mark Hofmann, confirmed this concern in his January 31, 1994, letter to the editor of *Aviation Week & Space Technology*, saying, "one major concern relates to deciding what aviation tasks and *functions* now being performed by humans should be automated. Such decisions should be based on enhancing overall system performance and helping the human to be more accurate and productive. Another concern is the availability and use of information by operators and maintainers due to the overwhelming pace and volume of data flow." The poignant cockpit voice recording of the last two minutes of the fatal China Airlines Flight 140 transcribed in the May 23, 1994, issue of *Aviation Week & Space Technology* provides a clear statement of the problem: "... the crew was making decisions that ran contrary to the reasoning of the aircraft system's automated logic." McDaniel (1988) cites other automation-related air disasters and elaborates on how these relate to allocation of functions and automation.

Many believe effective function allocation is the key process that has the greatest potential for solving these types of problems. Every level of the military's system acquisition process references function analysis/allocation. The different levels in the system acquisition chain make different uses of function analysis/allocation, however, and have customized the definition of function allocation for their own purposes. This paper reviews function allocation from the perspective of different levels, from top-level management in the US Department of Defense (DoD) down to the human factors engineers who support the program and laboratory scientists and engineers who develop new design aids.

The top-level model of how the US DoD and the US Air Force manage system acquisition includes function allocation as a means for selecting technologies that can be implemented to satisfy overall system-level requirements. At the bottom of the acquisition pyramid, the human factors engineers supporting the development programs think of function allocation as a process for assigning functions or subfunctions to automation or a human operator.

Today, multifunction controls and displays, multiple interconnected processors, and the need for a truly integrated crew system create engineering demands that are not being met effectively. Automation is often recommended as the solution to operator workload problems, but we are beginning to realize that problems with inconsistent implementation of automation are emerging as the most significant human factors engineering nightmare. Traditional human factors engineering tools, such as the paper functional block diagram, are not able to deal with the multilevel complexity in the human-system interface. Modern crew system design is a complex issue that should not be addressed piecemeal but requires an integrated process and design support system to help manage the process. Improved function allocation techniques are necessary to efficiently guide the automation of crew system functions. New approaches to crew system design include computer tools to assist in the function allocation process and to relate function allocation to analysis of taskload and workload in complex systems. Some aspects of acquisition appear to be working against effective integration of the crew system. An analysis of cockpit design procedures in current use for military aircraft revealed that the aviation industry's cockpit design process was fragmented across departments, primarily according to the cost centers associated with the Work Breakdown Structure (WBS) and, secondly, according to the components acquired directly by the government on other contracts and provided to the prime contractor as a component of the new system.

TOP MANAGEMENT VIEW OF FUNCTION ALLOCATION

Military system planners think of design and function allocation as a process to select a capability that best meets the needs of a system. *Acquisition* is the term the military uses to describe the process for developing and obtaining new systems. Acquisition is defined as "a

directed funded effort that is designed to provide a new or improved material capability in response to a validated need," (US Dept. of Defense [DoD], Directive 5000.1, *Defense Acquisition*, February 1991). This same document describes a *weapon system* as "the prime operating equipment and all of the ancillary *functions* that comprise the maintenance capability, training, technical orders, facilities, supplies, spares, manpower, and anything else needed to provide an operational capability." Because modern weapon systems are complex beyond comprehension, the military's system acquisition process is almost as complex, requiring documents of hundreds of pages to fully describe it. Within the context of system acquisition, *systems engineering* is the term used to describe managing a development.

MIL-STD-499B, Systems Engineering (US DoD, July 1994, formerly titled *Engineering Management*), defines *systems engineering* as: "an interdisciplinary approach to evolve and verify an integrated and life-cycle balanced set of system product and process solutions that satisfy customer needs. Systems engineering (a) encompasses the scientific and engineering efforts related to the development, manufacturing, verification, deployment, operations, support, and disposal of system products and processes, (b) develops needed user training equipment, procedures, and data, (c) establishes and maintains configuration management of the system, (d) develops work breakdown structures and statements of work, and (e) provides information for management decision making."

The military's model process for systems engineering is shown in Figure 5.1.

From the viewpoint of top management, function analysis/allocation is not defined in terms of allocating functions to operators or automation. Rather, *function analysis/allocation* is a top-down approach that decomposes function requirements to ever lower levels of detail—that is, a flow-down of requirements—until synthesis of solutions can occur. Once functions have been decomposed to lower levels, requirements are allocated to proposed *configuration items* (a term used to describe the low-level products in the WBS). The government model for systems engineering intentionally avoids terms that involve uncertainty, such as "innovation, creativity, or invention." Creativity and invention are assumed to occur within industry. The management process involves trade-offs among alternatives and selection of the approach that best

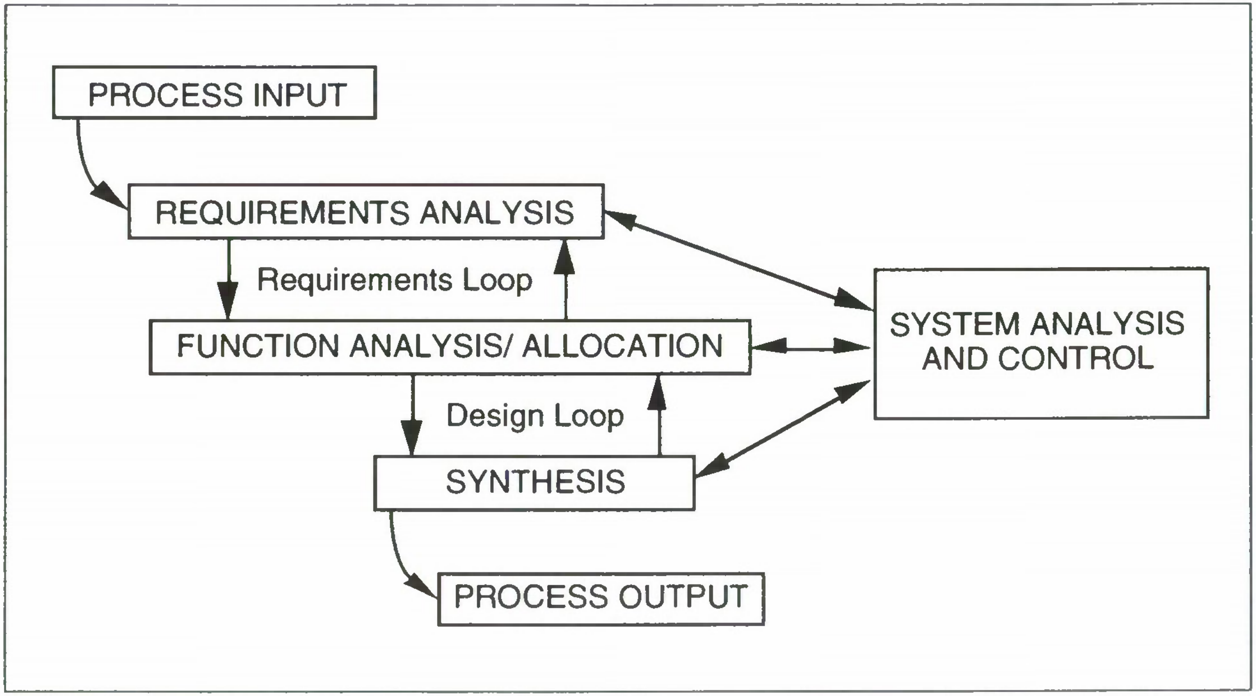


Figure 5.1. The systems engineering process.

meets the requirements. The block titled "System analysis and control" refers to progress, cost, and schedule audits.

Synthesis is defined as the translation of functions and requirements into possible solutions. Synthesis is as close as the process comes to referencing innovation. Synthesis is conducted iteratively (the "Design loop" in Figure 5.1) with functional analysis/allocation to define a complete set of functional and performance requirements necessary for the level of the design output required and with requirements analysis to verify that solution outputs can satisfy customer input requirements.

The iterative design loop includes the crew system, but it is generic and relates to all system-level requirements. "Turning the crank" is the phrase one often hears used to refer to the process of making this design loop generate the design alternatives and compare them with requirements. When the crank is turned, alternatives are generated, evaluated, and finally accepted or rejected based on formal and structured criteria derived from requirements.

CREW SYSTEM DESIGN VERSUS THE WORK BREAKDOWN STRUCTURE

One of the greatest impediments to integrating crew system functions may be the WBS for aircraft systems in the military standard *Work Breakdown Structure for Defense Materiel Items, MIL-STD-881B* (US DoD, March 25, 1993). The WBS is prescribed for use on new system acquisitions to aid definition, analysis, tracking, and control of each component of the system throughout the development period. The WBS is a hierarchical diagram that decomposes the entire system into components, subcomponents, subsubcomponents, etc., down to the level of each module of hardware, software, services, data, training, support equipment, management, and other work tasks. The WBS structure, in use since the early 1970s, has not evolved with hardware and software technology and has yet to recognize the crew system as an important component of an aircraft.

The military's solicitation for a new system includes the first three levels of the WBS hierarchy, as tailored from a model prescribed in *MIL-STD-881B*. In the jargon of standards, "tailoring" usually means deleting nonapplicable material, but not adding material. As part of their proposals, contractors expand the WBS by developing the lower levels of the WBS hierarchy. The total WBS becomes part of the con-

tract and directs the prosecution of the program from that time onward. In the WBS model for an aircraft, level 1 has but a single element, the entire aircraft system; level 2 has ten elements: air vehicle, systems engineering/program management, system test and evaluation, training, data, peculiar support equipment, common support equipment, operational/site activation, industrial facilities, and initial spares/repair parts. The air vehicle is subdivided into level-3 elements, including the airframe, propulsion, software, etc.

The WBS provides a consistent mechanism for tracking all the subcontracts and vendors contributing to the system. Its most important function is in tracking the cost and progress of each element, providing baseline data for estimating what the elements should cost and how long the development should take. The WBS, or something like it, is essential to managing the development of a major system. By assuming an obsolete structure of design priorities, however, the WBS unintentionally hinders effective function allocation. The problem is that the crew system is not defined as an identifiable component of the aircraft in the WBS, but is scattered among twelve of the seventeen level-3 elements under the level-2 air vehicle WBS element.

Below are excerpts of these from *MIL-STD-881B* (condensed and edited for clarity):

"*Level 3 Airframe* includes support subsystems essential to the designated mission requirements, manual flight control system, fuel management system, furnishings (i.e., crew, cargo, passenger, troop, etc.), instruments (i.e., flight, navigation, engine, etc.), life support and personal equipment.

"*Level 3 Propulsion* includes engine control units, if furnished as an integral part of the propulsion unit.

"*Level 3 Air Vehicle Applications Software* includes all the software that is specifically produced for the functional use of a computer system or multiplex data base in the air vehicle.

"*Level 3 Air Vehicle System Software* includes software for specific computer system or family of computer systems to facilitate the operation and maintenance of the computer system and associated programs for the air vehicle.

"*Level 3 Communications/Identification* refers to that equipment (hardware/software) installed in the air vehicle for communications and identification purposes. It includes, for example, intercoms, radio sys-

tem(s), friend-or-foe identification equipment, data links, and control boxes associated with the specific equipment.

"*Level 3 Navigation/Guidance* refers to that equipment (hardware/software) installed in the air vehicle to perform the navigational guidance function. This element includes, for example, radar, radio, or other essential navigation equipment, radar altimeter, direction finding set, Doppler compass, computer, and other equipment homogeneous to the navigation/guidance function.

"*Level 3 Central Computer* refers to the master data-processing unit(s) responsible for coordinating and directing the major avionic mission systems.

"*Level 3 Fire Control* refers to that equipment (hardware/software) installed in the air vehicle which provides the intelligence necessary for weapons delivery such as bombing, launching, and firing. This element includes, for example, dedicated displays, scopes, or sights; and bombing computer and control and safety devices.

"*Level 3 Data Display and Controls* refers to that equipment (hardware/software) which provides visual presentation of processed data by specially designed electronic devices through interconnection (on or off line) with computer or component equipment, and associated equipment needed to control the presentation of data. This element provides the necessary flight and tactical information to the crew for efficient management of the aircraft during all segments of the mission profile under day and night all-weather conditions. Excluded are indicators/instruments not controlled by keyboard via the multiplex data bus and panels and consoles that are included under the airframe.

"*Level 3 Survivability* refers to that equipment (hardware/software) which assists in penetration for mission for ferret and search receivers, warning devices, and other electronic devices, electronic countermeasures, jamming transmitters, chaff, infrared jammers, terrain-following radar, and other devices typical of this mission function.

"*Level 3 Reconnaissance* refers to that equipment (hardware/software) for photographic, electronic, infrared, and other sensors; search receivers; recorders; warning devices; magazines; and data link.

"*Level 3 Automatic Flight Control* refers to those electronic devices and sensors which enable the crew to control the flight path of the aircraft as well as to provide lift, drag, trim, or conversion effects. This element includes flight control computers, software, signal processors,

and data transmitting elements that are devoted to processing data for either primary or automatic flight control functions."

The dispersion of crew system design functions across these elements has a significance that reaches far beyond cost accounting. The WBS itself allocates design requirements to specific organizations responsible for their development. In practice, the WBS has influenced the organizational structure of both the military program and the contractor. Responding to the product structure in the WBS, industry has organized into departments that correspond to each of these products, with a separate department head responsible to the contractor's program manager for those specific products.

Since the WBS model has no element for crew system, industry has no department head responsible for the crew system. Because of this structure, crew system integration requires coordination between several departments within the company. Integration is further hindered because many of the WBS elements are subcontracted out to other companies, with the prime contractor serving as the sole coordinating agent. Decisions made within individual departments can adversely effect the crew system function allocation without other departments' being aware of a problem until it is too late to correct it.

So far, attempts to modify the standard to consolidate and integrate the crew system into a single level-3 WBS element have failed. As far back as May 1987, a triservice laboratory study panel proposed a change to *MIL-STD-881A* (the version of the standard preceding *MIL-STD-881B*) to a group of triservice aeronautical commanders. While the commanders supported this proposal, it was subsequently killed by the cost-accounting officials who control the standard on the grounds that it would ruin their traceability and prediction models. This is a major change, for it involves more than adding a new element called "crew system"; it also involves removing those functions from the existing twelve elements. This proposal would cause a significant reorganization of industry, removing some of the traditional responsibilities from these department managers.

While the WBS is unquestionably necessary for developing new systems, the hierarchical structure has not evolved to reflect adequately the way in which modern technology has changed the nature of the aircraft. When the WBS process began back in the early 1970s, the pilot's crew station was composed of several independent subsystems, usually supplied by different subcontractors. Then, it was the prime contractor's job

to locate each of these subsystems in the aircraft. In the context of the cockpit design, the prime contractor's effort centered on the cockpit layout and installation of controls and displays, with less attention to functionality. The traditional cockpit design was a drawing of a cockpit showing the location of the seat, control panels, controls, and displays. The cockpit drawings showed the sizes, shapes, and even labels for every control and display. This one drawing could depict the entire human-system interface. The information interface was explicit in the labeling of the controls and mechanical displays. Even the workload evaluations of that era were based on hand-travel and eye-travel distances, rather than the mental difficulty of the task.

Modern cockpits have an almost generic physical appearance, clean and uncluttered, consisting of a few multifunction controls and a few multifunction displays (CRTs, LCDs, or similar). Today, the critical design issues in the aircraft cockpit relate to information management and integration of data. Because of the massive amount of information flowing through the crew system, function analysis/allocation is critical to the effective integration of the modern cockpit. The pilots' demands for more situation awareness are eagerly met by new technology that can layer more and more data on the multifunction displays, so that merely accessing the data has become a time-consuming and complex task in itself. As a result, pilot workload has increased.

GENERAL REQUIREMENTS FOR FUNCTION ANALYSIS/ALLOCATION

The US Army, Navy, and Air Force jointly developed *MIL-STD-46855, Human Factors Engineering Requirements for Military Systems, Equipment and Facilities* (US DoD, May 26, 1994), as the primary human factors engineering tasking document for the three services. In use since January 1979, this general-purpose standard establishes and defines the requirements for applying human work to be followed by a contractor or subcontractor. Tailoring and citing this document in a contract is the primary way the military tells the contractor how much and what kind of human factors engineering effort is expected. The process of function analysis/allocation is the heart of *MIL-STD-46855*, as demonstrated by the following excerpts (paragraph numbers omitted, italics added):

"*Defining and Allocating System Functions.* The *functions* that must be performed by the system in achieving its objective(s) within specified mission environments shall be analyzed. Human factors engineering principles and criteria shall be applied to specify human-system performance requirements for system operation, maintenance and control *functions* and to *allocate system functions* to (1) automated operation/maintenance, (2) manual operation/ maintenance, or (3) some combination thereof. *Function allocation* is an iterative process achieving the level of detail appropriate for the level of system definition.

"*Information Flow and Processing Analysis.* Analyses shall be performed to determine basic information flow and processing required to accomplish the system objective and include decisions and operations without reference to any specific machine implementation or level of human involvement.

"*Estimates of Potential Operator/Maintainer Processing Capabilities.* Plausible human roles (e.g., operator, maintainer, programmer, decision maker, communicator, monitor) in the system shall be identified. Estimates of processing capability in terms of *workload*, accuracy, rate, and time delay should be prepared for each potential operator/maintainer information processing *function*. Comparable estimates of equipment capability shall also be made. These estimates shall be used initially in determining *allocation of functions* and shall later be refined at appropriate times for use in definition of operator/maintainer information requirements and control, display and communication requirements. In addition, estimates shall be made of the effects on these capabilities likely to result from implementation or non-implementation of human factors engineering design recommendations. Results from studies in accordance with 5.2.1 may be used as supportive inputs for these estimates.

"*Allocation of Functions.* From projected operator/maintainer performance data, estimated cost data, and known constraints, analyses and trade off studies shall be conducted to determine which system *functions* should be machine-implemented or software controlled and which should be reserved for the human operator/maintainer. *Allocation of functions* shall consider the risks of making an incorrect decision for each alternative being evaluated so that designs may be simplified or enhanced to prevent or minimize situations where human decisions are made under conditions of uncertainty, time stress, or *workload* stress. The possibility of influencing human or equipment capabilities through

personnel selection and training as well as through equipment and procedure design shall be considered, and the costs of such action shall be considered in trade-off and cost-benefit studies."

MIL-STD-46855 uses the same functional hierarchy defined in several triservice standards, *MIL-STD-1908, Definitions of Human Factors Terms* (US DoD, December 24, 1992), *MIL-STD-1388-1A, Logistic Support Analysis* (US DoD, April 11, 1983), and the Army's *MIL-STD-1478, Task Performance Analysis* (US DoD, May 13, 1991). Figure 5.2 shows this hierarchy compared to the one typically used in crew system design. The Logistics Support Analysis computes the requirements for MPT (manpower, or the number of people; personnel, the job titles; and training), hence the inclusion of the items "Job" and "Duty." While they have similar names, this hierarchy differs from the hierarchy used in aircraft development described below. The triservice term "Job," for example, would refer to a pilot, and "Duty" would refer to flying the aircraft.

In the general-purpose hierarchy, "Mission," "Scenario," and "Function" are major command functions and do not correspond to any terms used in crew system development. The lower-level terms, "Task," "Subtask," and "Task element" in the *MIL-STD-46855* structure are similar to "Function," "Subfunction," and "Task" definitions of the aircraft development structure.

AIR FORCE IMPLEMENTATION OF FUNCTION ALLOCATION

While the triservice *MIL-STD-46855* was designed to be generic and applicable to all systems, the Air Force has developed its own special-purpose standard tailored to the supercritical needs of the aircraft crew system: *MIL-STD-1776A, Aircrew Station and Passenger Accommodations* (US DoD, February 25, 1994). Section 4.1 of this document contains a Crew System Development Process (CSDP), which is tailored for complicated aircraft cockpits. The application guidance for the process notes (italics added): "It is recognized that designs do not start from 'scratch' but that a baseline (or similar) system is typically used from which to make improvements. The *function analysis* analyzes the events identified in the mission analysis and defines *functions* that the aircraft system has to perform in order to complete the mission. The

GENERAL PURPOSE SYSTEM	AIRCRAFT SYSTEM
Mission	Mission phase
Scenario/Condition	Mission event
Function	Function
Job	Subfunction
Duty	Subfunction
Task	. . . (subfunctions as required)
Subtask	Task
Task element	

Figure 5.2. General-purpose functional hierarchy defined in several triservice standards (left) and functional hierarchy typically used in crew system design (right).

functions are then *allocated* to be performed by the aircrew or other subsystems within the aircraft.... Included in the *function allocation* process is the analysis of the information requirements of the aircrew in order to complete the mission. Control and display parameters are then identified to provide adequate information transmission between the aircrew and aircraft in order for the aircrew to perform the *functions allocated* to the aircrew subsystem. Based on these parameters, and the rest of the aircrew system implementation, task load, and workload for a given aircrew station can be analyzed."

This process calls for verifying the effectiveness of the design by "reviewing the analyses as they are developed, observing the mock-up and simulation demonstrations, and reviewing simulation test plans and results." The process also requires the generation and submission of reports in the formats specified in *MIL-STD-46855*.

Section 4.1.3 of *MIL-STD-1776A* has detailed requirements for function allocation: "*Functions allocated* to the aircrew shall identify which aircrew member performs that *function*. For *functions* assigned jointly to the aircrew and another aircraft subsystem and/or to more than one aircrew member, the subsystem or aircrew member which has primary responsibility for performing the *function* and the subsystem or aircrew member which has secondary responsibility for performing the *function* shall be identified. Functions may be *allocated* to more than one type of implementation. Functions may also be *allocated* to more than one subsystem." For practicality, it is also recognized that "program schedule and resource constraints restrict designers to analyze only the problem areas perceived to be the most difficult." To conserve resources, new function analyses often use segments of old function analyses from the baseline system to fill in the gaps between the new, critical, or difficult functions of the new design. In many cases, functions in new systems are allocated as they were in the baseline system, particularly if the baseline functions were free of problems. Appendix C of *MIL-STD-1776A* contains a thirty-page instruction for integrating the CSDP into the Systems Engineering Master Plan (SEMP) and Systems Engineering Master Schedule (SEMS), which integrate all development activities. This process emphasizes the integrated product team (IPT) approach and describes how the various teams interact to coordinate the entire system.

SYSTEM DEVELOPER'S VIEW OF FUNCTION ALLOCATION

When the Air Force begins to acquire a new aircraft or make a major modification to an existing aircraft, a system program office (SPO) is established by bringing members of various disciplines together as a team. These SPOs are located at Wright-Patterson Air Force Base to be near the research and development expertise centered in the laboratories also located there. This SPO team translates the operational requirements into a contract and later manages that contract. Typically, the Air Force contracts with industry for aircraft design and production. Similarly, the engineering part of function analysis/allocation is contracted to industry as part of the overall system development. The official involvement of military personnel in the process is to monitor industry's efforts.

The contract tasks industry to perform function analysis/allocation in one of two ways. The first way is by requiring the contractor to perform a human factors engineering program in accordance with *MIL-STD-46855* and/or *MIL-STD-1776A*, both of which include instructions for performing function analysis/allocation. The second method is to insert specific requirements for performing function analysis/allocation into the contract Statement of Work. Either way, the military (program officials from the SPO and pilots from the using command) participate by reviewing the contractor's products at design reviews, attending mock-up reviews, and observing simulations of the crew system. The format and contents of the function analysis/allocation vary from one company to another, and its quality depends largely on the expertise of company engineers and the resources available for the effort. The function analysis/allocation is not an end in itself, but a means to acquiring an effective and efficient system.

To implement the IPT approach to system development, the Air Force's on-going F-22 program has made a radical departure from the WBS model in *MIL-STD-881*. Using its prerogative to "tailor" the model WBS, the F-22 SPO completely overhauled it and made the "cockpit system IPT" one of eight level-3 elements in the WBS (one element for each of the eight IPTs). The cockpit system element is subdivided into five subelements: pilot-vehicle interface (PVI), aircrew station accommodations, escape, life support, and canopy. The F-22 program did not make a total break with the traditional WBS model,

however, for another level-3 element is avionics, which contains the avionics controls and displays hardware. Notwithstanding this exception, the F-22 program is the first military program to experiment with such a high level of integration of the crew system design activities. The results to date indicate this approach to be far superior to the traditional WBS, providing high visibility to crew system issues and getting problems resolved in favor of the pilot.

The specific definition of the cockpit system element used by the F-22 program is as follows: "This element comprises the systems and equipment that provide the pilot the capability to manage the aircraft subsystems and to function within the aircraft performance and threat envelope. This includes the pilot-vehicle interface, crew station design, life support, escape systems and human engineering/crew vehicle interface (CVI), and the canopy system. This element includes the coordinated functional efforts of the Cockpit Integrated Product Team associated with the task for each of the subelements listed above, including the tasks related to analysis, design, development, test, qualification, fabrication, assembly, installation, integration, verification, and documentation. Included as part of each subelement is the application of human engineering principles in the design and development process."

The function analysis/allocation process provides the key for military and industry personnel to develop better crew systems. Acquisition regulations that prohibit military personnel from directing, managing, or supervising contractors create a barrier to technical discussions. The requirements included in the contract's Statement of Work and specification are deliberately general so as not to unnecessarily hinder the contractor from developing the best possible product. Within this context, the function analysis/allocation provides a valuable communications mechanism, so that industry can get a better understanding of how the military customer sees the contractor's design in the context of requirements and so that the military can get a better understanding of just what industry is planning to deliver. The function analysis/allocation turns out to be one of the most effective tools for understanding the crew system at a detailed level.

While most design and development work is done on contract by industry, there are occasions when quick reaction or restricted information requires that some design work, including function analysis/allocation, be done in-house. All of the aircraft SPOs are part of the Air Force's Aeronautical System Center (ASC). ASC also has the Crew Station

Evaluation Facility (CSEF). The CSEF performs a special design and evaluation role for some programs. For example, recently, the CSEF evaluated the functions of a KC-135 flight deck as part of a general redesign to eliminate the navigator position. After reallocating the navigator functions to the pilot and copilot, workload analysis revealed the need for automating some functions. The CSEF developed an alternative design and configured a two-place simulator to test the revised design. The CSEF has crew system simulators for several existing aircraft that are used to perform special studies. Pilot-in-the-loop simulator evaluation was then used to validate the conceptual design and demonstrate acceptable crew workload. This proof-of-concept became the foundation of requirements documents for the KC-135 system upgrade that was later contracted to industry. By testing certain concepts in-house, the CSEF helps the SPO develop more efficient contracts. The CSEF can work directly with other military personnel as part of an integrated product team, whereas contractors must be dealt with at arm's length through advance tasking on a contract and redirected only through a time-consuming, formal contract change.

LABORATORY VIEW OF FUNCTION ALLOCATION

In 1951, Paul M. Fitts, the founder of the Human Engineering Division of the US Air Force's Armstrong Laboratory, was the first to apply formal rules to function allocation in his list of those functions in which humans excel over machines and those functions in which machines excel. Today, similar listings are still called Fitts' lists. Because Fitts' functions are general in nature, they remain valid, for the most part. One might argue that remote-sensing technology now excels at detecting small amounts of energy, but recognition and identification continue to be better done by humans. The ability to store large amounts of data now favors the computer, but humans are still required to interpret and understand the nature of data.

Between 1984 and 1992, the Paul M. Fitts Human Engineering Division sponsored a three-phased contract effort called Cockpit Automation Technology (CAT) that involved five major aircraft companies (McDaniel, 1986; McDaniel, 1988; Kulwicki, McDaniel, & Guadagna, 1987). In the late 1980s, the work begun with the CAT effort was extended under a project named Crew-Centered Cockpit Design (CCCD) (Storey, Roundtree, Kulwicki, & Cohen, 1994). CCCD is developing a

new and integrated CSDP with formal procedures and tools for function analysis/allocation. Importantly, the CSDP methodology is implemented with CCCD's computer-based toolset providing support for the design of both new and upgraded crew systems. Martin (1994) described the application of the toolset in a sample F16 cockpit upgrade to illustrate the new process.

The CCCD process currently has about 120 activities, most supported by separate software design tools. It is beyond the scope of this paper to describe all of them. The 120 activities of the CSDP are divided into five categories: program planning/scheduling, requirements analysis and predesign, crew system analysis, crew system design, and crew system evaluation. The "crew system design" category accounts for the majority of the activities. A key element in this toolset is a structure and discipline to perform function analysis/allocation.

A survey of industry users by Lehman et al. (1994) revealed that the majority of aircraft manufacturers have developed their own rapid-prototyping simulators and make extensive use of simulation to verify the function allocation and assure that pilot workload is acceptable. The weakness of such simulation is that the data are almost entirely subjective, relying on critique by pilot subjects in the idealized ground-based simulation. Because of the critical role of the simulation, the industry human engineers are at the mercy of scarce, highly sophisticated programmers as well as electrical and hardware engineers to modify and run these simulators. Loss of access to key personnel because of higher priority projects can stop an evaluation. To prevent such limitations, the CSDP toolset is directly linked into a generic crew system simulator, called the Engineering Development Simulator (EDSim), which is reconfigurable without sophisticated programming support (Givens, 1994). Because the system is built with object-oriented software, a journeyman programmer can modify or even create a new display for the system. The EDSim is an integral part of the CSDP toolset, allowing the analytical tools and the EDSim to share data.

CCCD's CSDP is structured in accordance with the general guidelines in *MIL-STD-46855*, and even has utilities that generate reports in the format required by *MIL-STD-46855*. An earlier version of CCCD's CSDP was used as a model for the CSDP now included in *MIL-STD-1776A*, discussed above, and is compatible with the IPT concept of design support. The CSDP uses the aircraft function hierarchy in Figure 5.2. In this hierarchy, functions and subfunctions refer to activities that

must be accomplished, but without specifying how they will be performed. At the lowest level, after a function or subfunction is allocated to an operator or automation and is implemented with a specific procedure for accomplishing the function, it becomes a task.

The CCCD toolset contains specific aids to help with function analysis/allocation. At the top level, a Mission Decomposition Tool assists in identifying the top-level functions and assigning a target time line. To avoid mistakes caused when the designer assumes the role of the user, a new Concept Mapping technique allows the user to play the role of designer and effectively influence the function allocation and design decision making (McNeese et al., 1995). The Time Line Management Tool includes three modules: the Information and Control Requirements Analysis Tool, the Function Flow Analysis Tool, and the Function Allocation Trade Analysis Tool. These provide input to taskload and workload analysis programs.

CONCLUSIONS AND RECOMMENDATIONS

Mission analysis, function analysis, and function allocation have long been recognized as necessary to the design of complex systems. Yet, there has been little standardization in terminology, and many people use the terms *function* and *task* interchangeably. Attempts to cobble together taxonomies that serve both design and MPT purposes have disappointed both camps. At the crew system level, functions refer to specific activities that must be accomplished. The term *function allocation* refers to the process of assigning a function either to the operator(s) or to automation.

Function analysis has proven useful in detailing the requirements for components of a complex system, providing a common ground for understanding and communication among the members of the development team. The creation of an unified crew system design team to address all crew system issues marks an advance in the design process. Currently, the Air Force calls such teams *integrated product teams*. The F-22 SPO believes that IPTs have proved to be effective, and their use will likely continue and spread to other programs.

For new aircraft systems, piloted simulation continues to be the preferred method of testing the effectiveness of function allocation. Using simulators for testing is expensive and time consuming. In an attempt to reduce the cost of testing a design and to accomplish analysis earlier

in the design process, laboratory programs are attempting to develop analytical tools to support crew system design. The computer tools can share data where useful and minimize the labor of working with data. The difficulty in developing a computer tool to automate function allocation is in the implementation of the function. The problem is subtle, but highly significant. The most fundamental problem with function allocation is that its effectiveness cannot be evaluated at the *conceptual* level of the function. Analysis can only be carried out after the *implementation* of the function. A human operator and a machine will not perform a task the same way or at the same speed. It is axiomatic that only implemented functions can be assigned task times and their interaction with other functions assessed. Implemented functions should be called *tasks* to distinguish this characteristic.

Previous computer tools aimed at function analysis have failed because they try to analyze the function itself, rather than the implementation of the function (the task). The reason implementation of a function cannot be automated is that it is a creative and inventive process that involves application of specific technologies. To design, after all, is to *conceive and plan out in the mind.* After a function is allocated to an operator or automation, some creativity is required to implement it effectively into a human-system interface or some automated equipment. In practice, our inability objectively to prescribe the creative elements of function implementation has prevented totally automated analysis of design candidates.

Nor can function implementation be superficial. Functions can usually be implemented in more than one way, whether assigned to a human or to automation. Analysis can err when evaluating a sloppy or half-baked implementation. Frequently, when a new implementation is compared to an old implementation in a baseline system, the newly implemented function appears more efficient because some of the details were overlooked. Unless all function implementation alternatives are optimized to the same degree, there will be no equal basis for comparison. If functions are assigned to and implemented for a human operator, the effectiveness should be tested by a person who has first learned to operate the function with a reasonable proficiency. In a complex crew system, a function implementation should not be evaluated in isolation, but in the context of the total crew system in a realistic environment to judge the interactions of functions.

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REFERENCES

Fink, D. E. (1994, January 3). Human factors research must grow. *Aviation Week & Space Technology, 140*(1), 66.

Fitts, P. M. (Ed.). (1951). *Human engineering for an effective air-navigation and traffic-control system.* Washington, DC: National Research Council.

Givens, B. R. (1994). Object-oriented applications in a rapid prototyping environment. In *Proceedings of the IEEE 1994 National Aerospace and Electronics Conference* (Vol 2, pp. 814-819).

Hofmann, M. A. (1994, January 31). Human factors concerns mount. *Aviation Week & Space Technology, 140*(5), 6.

Kulwicki, P. V., McDaniel, J. W., & Guadagna, L. M. (1987). Advanced development of a cockpit automation design support system: The design, development and testing of complex avionics systems. In *Proceedings of AGARD Conference No. 417* (pp. 19-1–19-8.

Lehman, E., Roundtree, M., Jackson, K., Storey, B., Kulwicki, P., & Cohen, J. (1994). *Industry review of a crew-centered cockpit design process and toolset* (AL/CF-TR-1994-0063). Wright-Patterson AFB, OH: Armstrong Laboratory.

Martin, C. D. (1994). Development of a process for cockpit design. In *Proceedings of the IEEE 1994 National Aerospace and Electronics Conference* (Vol. 2, pp. 701-708).

McDaniel, J. W. (1986). Cockpit automation technology: A process for designing advanced aircraft systems. In D. J. Oborne (Ed.), *Contemporary ergonomics: Proceedings of the Ergonomics Society, 1986 Annual Conference, Durham, England, 8-11 April* (pp. 143-147). London: Taylor and Francis.

McDaniel, J. W., (1988). Rules for fighter cockpit automation. In *Proceedings of the IEEE 1988 National Aerospace and Electronics Conference* (Vol. 3, pp. 831-838).

McNeese, M. D., Zaff, B. S., Citera, M., Brown, C. E., & Whitaker, R. (in press). AKADAM: Eliciting user knowledge to support participatory ergonomics. *International Journal of Industrial Ergonomics.*

New CAL 140 transcript. (1994, May 23). *Aviation Week & Space Technology, 140*(21), 32.

Sparaco, P. (1994, January 3). Human factors cited in French A320 crash. *Aviation Week & Space Technology, 140*(1), 30.

Storey, B. A., Roundtree, M. E., Kulwicki, P. V., & Cohen, J. B. (1994). Development of a process for cockpit design. In *Proceedings of the IEEE 1994 National Aerospace and Electronics Conference* (Vol. 2, pp. 688-695).

US Department of Defense. (1983, April 11). *Logistic support analysis* (MIL-STD-1388-1A). Washington, DC: Department of Defense.

US Department of Defense. (1991, February). *Defense acquisition* (Directive 5000.1). Washington, DC: Department of Defense.

US Department of Defense. (1991, May 13). *Task performance analysis* (MIL-STD-1478). Washington, DC: Department of Defense.

US Department of Defense. (1992, December 24). *Definitions of human factors terms* (MIL-STD-1908). Washington, DC: Department of Defense.

US Department of Defense. (1993, March 25). *Work breakdown structure for defense materiel items* (MIL-STD-881B). Washington, DC: Department of Defense.

US Department of Defense. (1994, February 25). *Aircrew station and passenger accommodations* (MIL-STD-1776A). Washington, DC: Department of Defense.

US Department of Defense. (1994, May 26). *Human factors engineering requirements for military systems, equipment and facilities* (MIL-STD-46855). Washington, DC: Department of Defense.

US Department of Defense. (1994, July). *Systems engineering* (MIL-STD-499B [Draft]). Washington, DC: Department of Defense.

6

THE FUNCTION ALLOCATION PROCESS AND MODERN SYSTEM/SOFTWARE ENGINEERING

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In system/software engineering, function allocation is considered an inherent part of design; in human engineering, on the other hand, function allocation is viewed as a discrete step in system development. Simulation of behavior models representing alternative allocations is the most important analytical technique used for function allocation in system/software engineering. A major issue affecting the function allocation process is the quality of the modelling of system behavior. The use of formal languages for behavior modelling as well as object orientation are increasingly important in system/software engineering. Certain techniques and principles used for software development are also relevant for allocation between human and machine. It is suggested that some of these system engineering and software engineering developments should be considered within human engineering in order to advance the integration of system development efforts and to improve the function allocation process.

INTRODUCTION

In human factors engineering, function allocation to human or machine is considered a main step of system development, and a number of function allocation techniques have been proposed. The role of function allocation seems to be much less pronounced in system/software engineering, and function allocation is usually considered as an inherent part of design. This paper discusses the issue of allocation in the system development process in general and how modern system/software engi-

neering practices might affect function allocation within human factors engineering in the future. System modelling and, in particular, object-oriented techniques, are addressed. Function allocation within human factors engineering is briefly introduced before function allocation within system/software engineering is described in some detail. It is concluded that system/software engineering puts less emphasis on the allocation itself and more on the analysis and evaluation of the allocation decisions. For human factors engineering to be able to take advantage of the advances in modern system/software engineering, an important issue is how the modelling concepts used within system/software engineering are applicable for modelling of the complete human-machine system.

ALLOCATION WITHIN THE SYSTEM DEVELOPMENT PROCESS

A behavior model of the system is the main result from the initial system/software engineering effort. The mission and scenario analyses and the subsequent function analysis result in a description of the desired functional, or behavioral, characteristics of the proposed system. A function represents a logical unit of what we denote as the *behavior model*. The term *behavior* refers to both the human and the machine parts of the system and is used in the system/software engineering sense of the word; that is, behavior is defined by a system's inputs, outputs, and states as a function of time according to certain performance requirements. Later, we will discuss necessary ingredients of this model in the context of function allocation.

Functional analysis is concerned with decomposition of functional requirements and behavior. In parallel with the function analysis, system components and their hierarchy are identified in what we denote as the *component model*. In order to analyze functions in a meaningful way, it is usually necessary to consider the main characteristics of these system components. A component is, in general, an abstract concept, but at a certain level of detail will be associated with real components. The main types of system components are humans (liveware), hardware, and software.

The mapping of the behavior model onto the component model is called *function allocation*. This mapping implicitly establishes the links between the components and the required behavior of the inter-

faces. The main types of interfaces are human-human, human-machine, and machine-machine. Interface characteristics such as capacity of and delays on the links connecting the components must be considered. In practice, function analysis/function allocation is iterated until a real system that implements the required system behavior is proposed (Figure 6.1).

Information-processing capacity of the components is limited, and performance requirements associated with allocated behavior must be checked. Behavior must be specified in order to manage resources in situations with both normal and extreme workload. Various types of *nonfunctional requirements,* such as maintainability and redundancy, must also be considered. Components may fail in various ways. Thus, a failure mode effects analysis must be performed and then error detection and recovery requirements must be specified. The main goal of error handling is to return the system to its normal behavior. The systems engineer must be assisted by component specialist engineers of

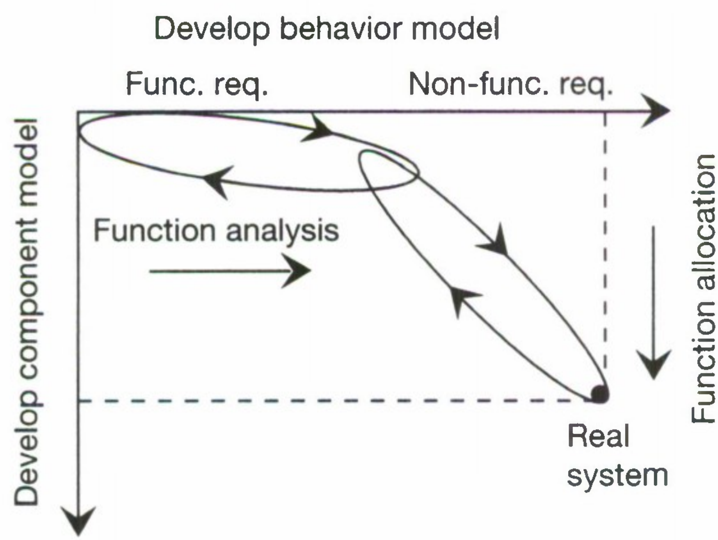

Figure 6.1. Combined development of behavior and component model.

various backgrounds in order to analyze the components' functional, interface, and nonfunctional requirements in detail. Consideration of all these requirements makes it necessary to extend and refinc the original behavior model. A new implementation-dependent model is then defined. The original model should be preserved, however, since it is easier to understand.

The implementation of the human-machine interface and the error handling at various levels often constitute more than half the software development effort. The fact that software often is the major cost item further emphasizes the importance of analyzing interfaces and nonfunctional requirements. An important motivation behind an analytical approach to function allocation is to reduce the number of changes to implementation (including prototypes) later in system development, thereby achieving cost savings.

MODELLING OF SYSTEMS

The requirements of a modelling language, in which the functional model is expressed, depend on the application domain and the purpose of the modelling. Approaches to modelling can differ in formality, abstraction, and perspective. The emphasis may be on the information processing involving complex data structures or on the dynamic aspects involving control sequences.

The importance of a defined syntax for the modelling language is widely recognized. A mutual understanding of the semantics (meaning) of the model among people (and computers) is also required. The need to develop formal descriptions is obvious from the system/software engineering point of view, and the primary example is, of course, programming. It is important to realize that a formal behavior model also can be executed in much the same manner as a program. There is often a conflict, however, between the desire to formalize and the need to understand the resulting description.

A function is usually conceived of as an information-processing activity. At a certain level in the description, we focus on the output and the required input and consider the function itself as a black box. The backbone of a behavior model is a hierarchy of functions decomposed to a level with which the designer is satisfied (Harel, 1992).

Data elements and stores are specified and associated with the input

and output flowing between functions (also denoted as *activities, actions, transformations,* or *processes*). This relationship between the functions is termed *data flow* and is usually depicted in data flow diagrams. It is important to realize that the data flow relation stipulates only that information *can* flow. Additional information is required to describe *when* this will happen and by *whom* the functions are performed. It can be argued that the semantics of functions and data flows are informal and therefore restrict analysis (Bræk & Haugen, 1993). A reader invariably associates sequences of processing with data flow diagrams, an interpretation that is invalid in principle and, more importantly, is potentially in conflict with the understanding of others involved in the development. Likewise, use of structured English to describe how functions transform the information is equally error prone without a rigorous definition of its semantics.

The (timewise) sequential relationships between functions are termed *control flow* and are mandatory in order to deal with real-time systems. *The main (or only) purpose of a number of functions will be to sense or control such dynamics.* The function analysis techniques reviewed by NATO Research Study Group 14 (RSG.14) (Beevis, 1992) focus on either the data flow or the control flow, *but only to a certain degree on both these dimensions.* In this paper, we consider behavior to include both data and control flow. The human is viewed as an event-sensitive information processor. A complete behavior model also includes information flow into and out of tasks, and sequencing and concurrency between tasks.

OBJECT-ORIENTED SYSTEM/SOFTWARE ENGINEERING

Jobling, Grant, Barker, and Townsend (1994) point out a major problem with traditional function decomposition. The decomposition violates the principle of dynamic system decomposition by attempting to model a dynamic system with a hierarchy of stateless functions and a global state reservoir from which any function may draw its inputs and into which it may deposit its outputs. That is, state and behavior are not preserved within the boundary of the decomposed functions. In object-oriented system/software engineering, this problem is addressed in a way that is more in accordance with a control engineering view of a

dynamic system. Other drawbacks of functional decomposition are the lack of support for instantiation and reuse of function types, which are concepts considered fundamental in object-oriented analysis and design.

The use of an object-oriented approach is currently expanding upwards into design and analysis (Coad & Yourdon, 1991; Rumbaugh, Blaha, Premerlani, Eddy, & Lorensen, 1991) and is often introduced as extensions to traditional techniques such as data flow diagrams. The focus of an object-oriented approach in systems analysis is typically on the roles and responsibilities of objects. An object is a concept, abstraction, or thing with crisp boundaries and meaning for the problem at hand. Objects serve two purposes:

- to promote understanding of the real world; and
- to provide a practical basis for computer implementation, i.e., behavior is allocated to an object.

An overview of object-oriented approaches can be found in Monarchi and Puhr (1992). The following discussion is based on Bræk and Haugen (1993) and Madsen, Møller-Pedersen, and Nygaard (1993). Traditionally, a number of techniques are utilized to manage complexity:

- abstraction (consider the whole system, but ignore aspects and remove implementation details);
- projection (the system is perceived from different angles, e.g., data and control flow views);
- aggregation and partitioning (e.g., functional or structural hierarchy).

Another powerful technique introduced in the object-oriented approach is generalization/specialization. This kind of complexity management is based on a description and understanding of individuals in terms of similarity by extracting general patterns of properties (types). Components of a system will be instances of these types. Instances and types are often referred to as *objects* and *classes* in object-oriented terminology. Types are made in two ways:

- by composition, i.e., aggregation of components that also may be instances of other types;
- by inheritance and specialization, i.e., a new type is defined by inheriting, specializing, and/or redefining the properties of an existing type.

Objects contain data items (called *attributes*), including state, and action sequences (called *methods* in object-oriented terminology) that process data items and received inputs. The use of methods provides a well-defined interface that hides the internal structure of data items and action sequences from the environment (encapsulates the object). Methods represent an object-oriented implementation of functions in data flow diagrams. It is important to realize that objects can execute action sequences *without* external stimulus. For example, actions can be executed periodically. Action sequences can be executed in coordination with other objects (using their methods), *alternately* (interleaved) with other objects (only one object active at a time), or *concurrently* with other objects (more than one object active at a time). The need for these types of action sequences can be illustrated by considering the modelling of a travel agent. The agent alternates between various sequential activities such as invoicing or making reservations, and the alternation is typically triggered by telephone interrupts. The agent can also perform tour planning together with a customer in the office, i.e., concurrently with the customer.

An object-oriented approach to system development typically concentrates on the development of an *object model*, that is, the creation of types (classes). The object model contains a description of types with their attributes and methods. The objects are linked by aggregation, inheritance, or other kinds of relations. The control flow is typically then described by *a dynamic model* based on finite-state machine formalism with various types of extensions. Finally, the information processing itself is described in what often is called the *functional model*. The object modelling technique (OMT) is an example of a technique using these three modelling projections (Rumbaugh et al., 1991).

Another object-oriented modelling method is SDL-92 (*s*pecification and *d*escription *l*anguage), which is a standard language for specifying and describing real-time systems used within the telecommunications community. In SDL, a system and its environment are conceived of as a structure of *blocks* connected by channels. Blocks can be decomposed, and their behavior is described in *processes*. Each process is modelled by an extended finite-state machine (EFSM), and communication between processes is possible only by signals that are produced and consumed by the EFSMs. A block type may be reused when a new block is defined. The new block inherits data, EFSM, and actions, which may then be (partly) redefined and/or extended. The ability to inherit and

modify behavior in this way is a powerful feature. Processes can be regarded as objects. In SDL, function allocation is performed as part of what is called *implementation design*. The result of the implementation design is a description of the system structure and its associated behavior. The function allocation is described by the relationship between the behavior description and the implementation description. SDL models can be executed and their implementation in software (or hardware) may be partly automated.

FUNCTION ALLOCATION TECHNIQUES IN HUMAN FACTORS ENGINEERING

Overviews of function allocation techniques used within human factors engineering can be found in Meister (1985), Rouse (1991), and Beevis (1992). The following summarizes an iterative approach to allocation advocated by Rouse (1991), which consists of three passes through the allocation, design, and evaluation sequence.

Comparative allocation approaches are first used in the *initial design phase*. Functions allocated to humans are then converted to tasks by designing displays, input devices, and operating procedures. Human performance and workload are predicted with emphasis on single-task performance/workload at different points in time. The *design integration phase* focuses on relationships between multiple tasks at similar points in time. Complementary tasks could point to more integrated displays, input devices, and/or procedures to improve performance and reduce workload, while conflicting tasks could indicate the need to redesign displays, input devices, and/or procedures. In the *final design phase*, earlier decisions are reviewed and possible use of dynamic allocation is investigated. Use of prototypes or human-in-the-loop simulators is considered necessary in order to evaluate the final allocation.

FUNCTION ALLOCATION WITHIN SYSTEM/SOFTWARE ENGINEERING

The term *function analysis* is well established within system/software engineering, in contrast with *function allocation*, which often is treated as part of "implementation design" and/or software design. (A database

search resulted in forty-four matches for *function allocation* alone, but none when the term was combined with *system* or *software engineering!*) Nevertheless, function allocation is implicit in distributed system design, hardware/software codesign, general and real-time software design, and distributed artificial intelligence (AI) system design. Since system/software engineering puts more emphasis on the evaluation of the design than on techniques for function allocation itself, techniques for computer systems performance analysis are also relevant.

DISTRIBUTED SYSTEM DESIGN

Today many functions are allocated to software to be run on a distributed computer system comprising a network of general-purpose computers. The allocation is often dynamic. Two or more computing resources are interconnected if they can communicate, that is, exchange messages. The *client-server model* is the most pervasive for interconnectivity (Nicol, Wilkes, & Manola, 1993). This model organizes a distributed system as a number of distributed server processes that offer various services to client processes across the network. Many experts now agree that modelling of a distributed system as a distributed collection of interacting objects is appropriate. Objects are clients and servers within the system according to the roles allocated to them.

HARDWARE/SOFTWARE CODESIGN

A prominent allocation problem facing system/software engineering is, of course, whether a function should be implemented in hardware (including firmware) or software. For most functions, the decision is clearcut. However, functions (or operations) that can be implemented in hardware or software or both are called hardware/software *codesign operations* (Woo, Dunlop, & Wolf, 1994). These types of functions are generally primitive, specialized, and have strict performance requirements. Effective partitioning (allocation) of codesign operations into hardware or software depends on many factors, including performance, cost, maintainability, flexibility, and size. The resulting trade-off analysis closely parallels the comparative or economical allocation techniques in human factors engineering (Rouse, 1991).

DISTRIBUTED AI SYSTEM DESIGN

Multiagent problem solving, a subfield of distributed AI, is concerned with coordination, task decomposition, *task allocation,* and interaction/communication among "intelligent" agents. An intelligent agent may be defined as an entity capable of performing at least one of the following: sensing, decision making, or acting. Agents may need to share knowledge, goals, and plans to achieve a single global objective or separate individual objectives that interact. Agents often need to reason about the coordination process and the intentions or beliefs of other agents. An object-oriented architecture is often used in multiagent systems. Objects, representing agents, communicate by asynchronous message passing, which in turn changes the internal state of the objects.

Multiagent planning tackles the problems of task decomposition and task allocation (i.e., finding agents that can execute the tasks). Agents must be capable of performing a task, have the necessary resources (e.g., time) and possess the required knowledge. Note that task allocation is itself a task and that tasks are allocated to agents in run time. A development framework for agent-oriented applications, CADDIE, has been developed, as reported by Farhoodi (1993). There are few examples of large-scale operational multiagent systems, however, and the technology must be considered immature.

SOFTWARE DESIGN

The main allocation problems in system/software engineering are the allocation of behavior to software components and the allocation of software components to various computers. The basic software components of traditional software engineering are *processes* (programs, tasks) with independent behavior that is built from *modules* (functions, subroutines, procedures). The basic components in object-oriented system/software engineering are objects and methods. An object might implement a process.

Various general guidelines to implementation design in software engineering have been proposed. The following are examples from Bræk and Haugen (1993):

- Analyze requirements for physical distribution of interfaces and services. Minimize the bandwidth needed over channels covering physical distances.
- Allocate processes to computers in such a way that the mean peak load on a single computer does not exceed about 30 percent of its total capacity.
- Ensure that response-time requirements are satisfied for time-critical sections by use of priority and isolation.
- Add redundant units and restructure system until reliability requirements are satisfied.

In order to cope with uncertain and increasing workload during the life cycle of a product, it is common to require a certain spare processing and memory capacity. The frequent use of such crude guidelines is an indication of the difficulties involved in predicting the performance by analytical means. Several guidelines concerning allocation of behavior to modules have also been proposed. The best known are (Yourdon, 1989):

- *Cohesion:* Measure of how well a particular module's contents, its code, and local data structures group together. Cohesion (measure of locality) should be maximized. Modules should perform only one or a small set of operations that are grouped for some logical (not arbitrary) reason.
- *Coupling*: Degree of interconnection between modules. Coupling should be minimized. When triggered, the module's operation should not depend on values in global data structures or inside other modules.

Similar guidelines have also been extended to object-oriented software engineering (Coad & Yourdon, 1991). The most important motivation behind these guidelines is not increased processing performance, but reduction of programming errors and improved maintainability (i.e., reduction of life-cycle cost).

REAL-TIME SOFTWARE DESIGN

The need for information processing in a real-time system varies in a more or less stochastic manner. Because system resources (such as processing capacity and memory) are finite, the allocation of these re-

sources to the processes performing the information processing must be managed in order to fulfil deadlines. This allocation is referred to as *scheduling* and is an important part of the operating-system software. Systems with absolute timing requirements are called *hard real-time systems*. There are two distinct approaches to scheduling in hard real-time systems: run-time scheduling (on-line scheduling, dynamic scheduling) and pre-run-time scheduling. The first requires that the schedule be calculated at run time and is very common in real-time systems. Advantages of this approach are flexibility and adaptability to changes in the environment. Disadvantages can be complexity and high run-time cost. In Xu and Parnas (1993), it is argued that, given certain reasonable assumptions, this type of scheduling cannot guarantee that all timing constraints will be satisfied. A mixed strategy including precalculated schedules (i.e., fixed allocation) in addition to run-time scheduling is necessary in order to fulfil absolute timing requirements.

EVALUATION

Performance analysis of computer systems (Jain, 1991) has several objectives:

- Determine the number and size of components (capacity planning).
- Evaluate design alternatives.
- Compare two or more existing systems.
- Determine optimal parameter values (system tuning).
- Identify performance bottlenecks.
- Characterize system workload.

There are three techniques for performance evaluation: analytical modelling, simulation and measurement. The latter requires the existence of a prototype, while the first two are *analytical* methods. The criteria for selecting an evaluation technique—for example, time, cost, and validity—parallel those used in human factors engineering in studies involving operators. The main advantage of simulation is that a sufficiently accurate evaluation might be achieved with limited time and cost. Collecting measurements from a complex distributed computer system is difficult due to lack of control of environmental parameters and might be compared with a human-in-the-loop simulator evaluation.

The increasing use of simulations at various levels, in order to *select* among alternatives, *validate* design solutions (are we building the

right system?) and *verify solutions* (are we building the system correctly?) is a major trend in system/software engineering. The trend concerning trade-off analysis is discussed in the RSG.14 report (Beevis, 1992).

DISCUSSION

Function allocation in itself is not a big issue in system/software engineering, and this seems to parallel the state of practice concerning function allocation within human factors engineering as reported by RSG.14 (Beevis, 1992). The allocation of functions to human and machine seems to depend on both a formal analysis and prototyping. The general agreement is that the success of allocation decisions concerning operators depends heavily on the implementation and that a prototype or, rather, an operational system is required to determine its success.

The dichotomy between human and machine in function allocation seems somewhat artificial, since functions usually are shared in some way or another. The main assumption underlying so-called human-centered system design is that people are responsible for system objectives (at some operational level). The implication with regard to design objectives is therefore to support humans in achieving the operational objectives for which they are responsible (Rouse, 1991). Even though a function is allocated to the machine (automation), the operator will usually have a supervisory control role, with the possibility and the responsibility to intervene if necessary.

The allocation is often regarded as a mapping from the lowest-level functions to a set of system components. However, consider a function allocated to the operator. The operator will need a description of *what* to do (task analysis) and *how* (human-machine interface, procedures). But the operator should also know *why*, and this makes it necessary to consider functions (behavior, really) at one or more higher levels of abstraction. An operator performing a job consisting of a number of tasks and responsibilities needs a model of the system at various levels of abstraction. This type of knowledge is denoted as the operator's *internal model*. The need for behavioral and structural information at various levels is discussed by Rasmussen (1986) in what he terms the *abstraction hierarchy*. Likewise, the machine may need a model of the operator's behavior in order to provide adaptive aiding and an intelligent interface.

CONSEQUENCES OF SYSTEM/SOFTWARE ENGINEERING PRACTICES FOR FUNCTION ALLOCATION

Development of formal behavior models and their subsequent analysis is an important trend in system/software engineering. However, the human system component and the human's behavior are usually modelled only superficially. There is still a tendency within systems engineering to draw the system boundary too close to the machine and away from the human. The implications of the human-machine interface for the total operator job, or vice versa, are thus not analyzed sufficiently.

The attitude toward function allocation seems to be rather pragmatic in current system/software engineering practice. System/software engineers generally exploit technology as much as possible to increase the automation level, build a repertoire of decision aids, and make better and more intelligent human-machine interfaces. Partitioning of functions into more or less mutually exclusive human and machine sets is not really addressed. This coincides with modern human factors engineering views that such a partitioning does not take full advantage of overlap in intelligent capabilities between human and machine.

The impact of decision aids on system performance is rather difficult to analyze. Few software/system engineers consider the potential cost associated with the introduction of decision aids, for example, that operator workload and system performance (human and machine) will be a function of the reliance on the aid.

It is generally agreed that object-oriented development is bound to have a major influence on the manner in which systems are built (Loy, 1990). Differences in terminology and modelling practices among system/software engineers and human factors engineers might therefore increase, and in turn affect the function allocation process.

CONTRIBUTION OF SYSTEMS/SOFTWARE ENGINEERING TO FUNCTION ANALYSIS

The most promising developments with regard to formal behavior-modelling languages have come from the system/software engineering community. This is likely to be true in the future as well. A formal behavior model is an important input to function allocation. Further, allocation (and its basis) should also be described formally. This would

simplify analysis of the impact of changes during a system's lifetime and reuse of existing designs in new projects.

Whether human factors engineering can benefit from object-oriented system modelling techniques is still an open question. Proponents of an object-oriented approach to system development argue that the modelling concepts used in this approach more closely resemble the way humans organize knowledge and information; that is, object-oriented modelling concepts fit the internal model more closely. Modelling an operator actually means modelling the operator's internal model, so it could be hypothesized that object-oriented modelling concepts should be more suited for operator modelling.

Modern modelling languages in system/software engineering could be used to describe normative, rule-based operator behavior and the information needs of knowledge-based behavior. Note that we are talking about the capabilities of the modelling language. Identifying such operator behavior, however, is often difficult. In circumstances where the operator can be modelled as a computer system (of arbitrary complexity, if needed) and the crew as a distributed system, system/software engineering could possibly contribute with expertise.

Human engineering might benefit by modelling operators in terms of various behavior-modelling constructs in system/software engineering, such as alternation, concurrency, and inheritance. In some cases, behavior might be easier to understand if alternation or concurrency is used. For instance, alternation can simplify the description of interrupt handling.

A formal behavior model can be simulated directly and might itself include the details required to yield useful performance data comparable to a SAINT (Systems Analysis by Integrated Networks of Tasks) simulation. A more realistic scheme is automatic translation of a behavior model to a discrete-event simulation program to which more details can be added. This would enforce a certain consistency with the behavior model. Likewise, partly automatic generation of prototypes, necessary in order to evaluate function allocation, might be supported.

Traditional human factors engineering function allocation techniques based on comparison or cost will not necessarily result in a set of functions that are coherent and satisfactory to the operator. The guideline of assuring maximum cohesion, however, is to some degree consistent with the definition of a meaningful operator job. The minimal-coupling guideline, on the other hand, advocates a design that would isolate the

operator from the rest of the system and thus complicate updating of the operator's internal system model. The need to keep the operator in the loop requires a design that contradicts the minimal-coupling guideline. Allocation of functions for effective and cognitive support is suggested by Price (1985) as one of four allocation rules.

CONCLUSIONS

We see an increased interest in using object-oriented techniques in system and functional analysis. This will inevitably affect human engineering. For example, will function allocation and task analysis benefit from system functions modelled with object-oriented concepts? Will object-oriented concepts make it easier or more difficult to construct models of the human-machine system appropriate for typical human factors engineering activities? The claim that object-oriented modelling techniques map more closely to internal model constructs should be researched by human engineering. If this is valid, object-oriented modelling techniques could possibly have something to offer cognitive task analysis as well.

As we have seen, system/software engineering puts little emphasis on developing techniques and guidelines for function allocation. The reason, we believe, is that allocation decisions depend heavily on the application domain, the capability of the technology, and the constraints under which a system is developed. Techniques and guidelines applicable across a broad range of systems must necessarily be so general that they are of little value. Much more emphasis is put on techniques to evaluate and predict how a certain allocation of functions fulfils requirements. The main analytical techniques for these tasks are modelling and simulation. For human factors engineering to be able to adopt these analytical techniques for evaluation of function allocation decisions and design, models of cognitive operator tasks applicable for system development are much needed.

As human-machine systems steadily become more software intensive, it is important to see how the *complete human-machine system*, including the users, can be modelled and analyzed within the frameworks used by system/software engineering. A more comprehensive modelling of the human part of the system requires the expertise and involvement of human engineering. An integrated modelling and analysis, however,

would require, to a large extent, that human factors engineering use the same modelling languages as system/software engineering.

REFERENCES

Beevis, D. (Ed.). (1992). *Analysis techniques for man-machine systems design* (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

Bræk, R., & Haugen, Ø. (1993). *Engineering real time systems*. London: Prentice-Hall.

Coad, P., & Yourdon, E. (1991). *Object oriented design*. New York: Prentice-Hall.

Farhoodi, F. (1993). CADDIE—An advanced tool for organizational design and process modelling. In *Software assistance for business reengineering* (pp. 119-136). New York: Wiley.

Harel, D. (1992). Biting the silver bullet. Toward a brighter future for system development. *IEEE Computer*, 8-20.

Jain, R. (1991). *The art of computer systems performance analysis: Techniques for experimental design, measurement, simulation and modelling*. New York: Wiley.

Jobling, C. P., Grant, P. W., Barker, H. A., & Townsend, P. (1994). Object-oriented programming in control system design: A survey. *Automatica, 30*(8), 1221-1261.

Loy, P. H. (1990). A comparison of object-oriented and structured development methods. In R. H. Thayer & M. Dorfman (Eds.), *System and software requirements engineering*. Los Alamitos, CA: IEEE Computer Society Press.

Madsen, O. L., Møller-Pedersen, B., & Nygaard, K. (1993). *Object-oriented programming in the BETA programming language*. Wokingham, England: Addison-Wesley.

Meister, D. (1985). *Behavioral analysis and measurement methods*. New York: Wiley.

Monarchi, D. E., & Puhr, G. I. (1992). A research typology for object-oriented analysis and design. *Communications of the ACM, 35*(9), 35-47.

Nicol, J. R., Wilkes, C. T., & Manola, F. A. (1993, June). Object

orientation in heterogeneous distributed systems. *IEEE Computer*, 57-67.

Price, H. E. (1985). The allocation of functions in systems. *Human Factors, 27*(1), 33-45.

Rasmussen, J. (1986). *Information processing and human-machine interaction. An approach to cognitive engineering*. Amsterdam: North-Holland.

Rouse, W. B. (1991). *Design for success—A human centered approach to designing successful products and systems.* New York: Wiley.

Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F., & Lorensen, W. (1991). *Object-oriented modelling and design.* New York: Prentice-Hall.

Woo, N. S., Dunlop, A. E., & Wolf, W. (1994, January). Codesign from co-specification. *IEEE Computer,* 42-47.

Xu, J., & Parnas, D. L. (1993). On satisfying timing constraints in hard-real-time systems. *IEEE Transactions on Software Engineering, 19*(1), 70-84.

Yourdon, E. (1989). *Modern structured analysis.* Englewood Cliffs, NJ: Yourdon Press.

7

FUNCTION ALLOCATION IN INFORMATION SYSTEMS

G. U. Campbell and P. J. M. D. Essens

Function allocation is generally characterized as the process that assigns broadly defined activities to humans and machines in a system. Information software systems, as exemplified in command and control systems, require a different model of function allocation than do traditional human-machine systems. A two-stage process of function allocation was developed that adds support-based allocation to traditional human-machine allocation. In stage 1, focus is on human-computer strengths and weaknesses, but absolute and final allocations are not the goal. Rather, the results of stage 1 are used to address the requirement for the computer to support the human, a process that occurs iteratively with stage 2. The model was applied in the development of a Canadian Forces Artillery Regimental Data System.

INTRODUCTION

It has been noted by several authors (e.g., Meister, 1991) that the decisions concerning what to automate in software-based systems differ from the decisions made in more traditional human-machine systems. Traditionally, the allocations were treated as dichotomous decisions. In human-machine systems, if a function required lifting heavy weights or performing rapid calculations, then allocation could be assigned unambiguously to a machine. If complex pattern recognition was required, then the function was assigned just as unambiguously to the human operator. In software-based systems, automation relates less to labor and

far more to human information-processing and cognitive models. Specification of functions and tasks shifts toward a more cognitive focus.

Given this shift in focus, traditional function allocation is not appropriate in the development of software systems. Rather than discarding function allocation altogether, however, we can retain and enhance its value by adding new concepts. In the new conceptualization, the possible roles that the computer and the human can play in the developing system are of primary concern. Guidelines for defining such concepts should specify that the capabilitics of humans and machines should augment and enhance each other. Function allocation should be done on the basis of combined human-computer strengths and weaknesses, with the overriding goal being to optimize the performance of work. Three general allocation categories can be distinguished: operator primarily, human-machine mix, and machine primarily (Meister, 1985).

HUMAN-COMPUTER-PROCESS RELATIONSHIPS

Recently, concepts such as *support systems* and *joint systems* have become popular (Woods & Roth, 1988). Together with the concept of *supervisory systems* (Sheridan, 1988), these concepts address the relationship between the human and the computer in dealing with the proccsses they must control or manipulate. Four human-computer-process interactions can be distinguished (see Figure 7.1):

Split model. The split model represents the more traditional allocation approach in that the interaction with the process is statically divided between a human and a machine or computer.

Mediation model. In this model, the computer is the mediator between the human and the process. The mediation model is typical of supervisory control defined in the strict sense (Sheridan, 1987). Essentially, the computer acts on input from the process. In this conceptualization, the relationship bctween the computer and the human can havc several definitions. For example, this model includes the case where thc computer selects an action and informs the human, who can then opt to stop the process. Similarly, the computer may complete the entire job and inform the human of the results, if requested or required.

Support model. In thc support model, the human interacts with the process and the computer supports the human whenever the human

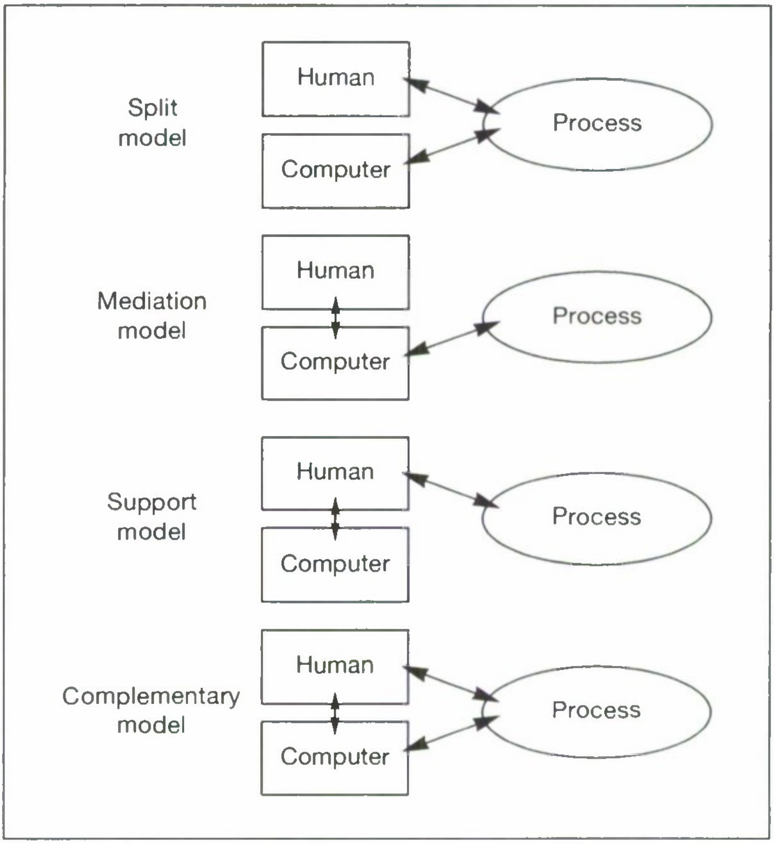

Figure 7.1. Roles of human and computer in handling the processes they control.

requests support. This tool-like configuration is characteristic of many decision-making situations. For example, an intelligence system that supports the commander in identifying enemy organizations by drawing from a database of past activities would be representative of this model.

Complementary model. In the complementary model, there is a shared role in managing the process. Both human and computer act on the process in a dynamic role allocation. The allocation is based on operational conditions, workloads, and priorities.

A fifth interaction model is also conceivable. In this final conceptualization, the human becomes the mediator and the computer dictates what should be done. This model is currently employed by some science-fiction writers.

The central issue is that conceptually different roles for computers and for humans are possible within a system. The concept of respective roles for humans and computers suggests specific allocation questions to be considered in the design of the system. Information systems that are emerging in command and control typically serve functions such as handling and storing large volumes of data and facilitating communications. At the same time, they provide opportunities for the introduction of support concepts in the command and control process. In these systems, one role of the computer is to support the human operator as described in the support model, above.

Software engineers are paying increased attention to and are more aware of the human operator as an integral part of system design. Attention to the operator as part of the system is a fundamental shift from the traditional engineering approach to integrated system development. Without an appropriate process, however, software system designers tend to focus on developing the elements of the system per se and pay scant attention to the tasks or cognitive models of the operators (Beevis, 1992). The two-stage function allocation process presented here helps designers focus on and address the role of the operator and the computer in the system in the light of the system goals that must be achieved. It encourages the designers to think in terms of supporting operators in their performance.

A TWO-STAGE FUNCTION ALLOCATION PROCESS

Although the multipurpose use of the computer in software systems allows roles to be combined in one machine, allocation decisions

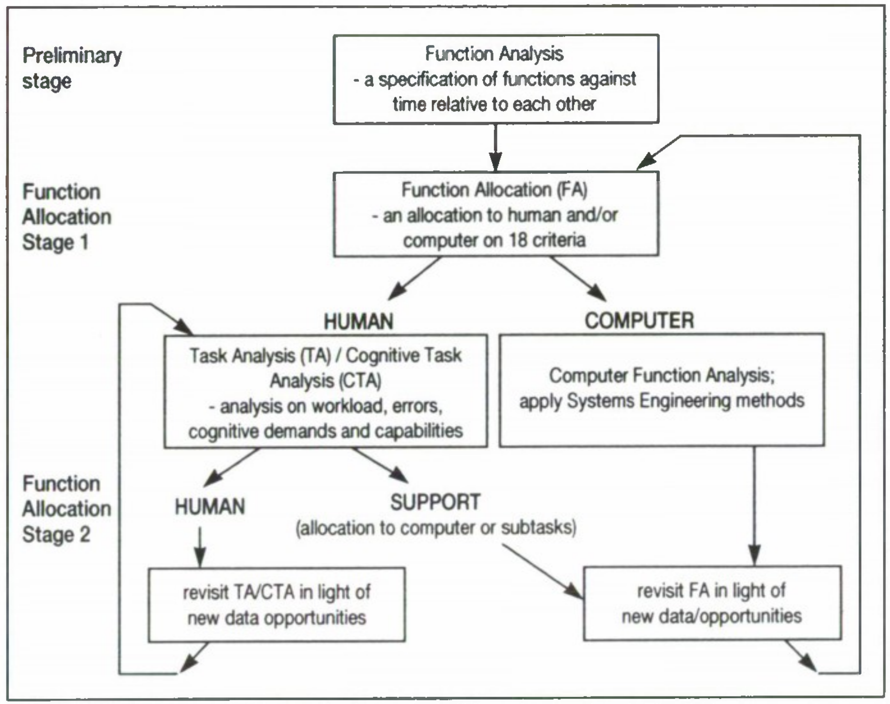

Figure 7.2. Two-stage model of function allocation in information systems.

should reflect and optimize the possible different roles of the human and the computer. Since one role of the computer is to support the human, allocation questions should address the capabilities and limitations of the human and the interaction with the process. To accommodate this concept of function allocation, an iterative process comprised of two stages is proposed here (see Figure 7.2). The two-stage process can be thought of as a way to integrate the split model and the support model. The first stage addresses the split model and the second stage addresses the support model. The result approximates a complementary model without discussing dynamic allocation but instead focusing on the roles of the human and computer and the integration of the models.

Preliminary Stage (function analysis). Prior to any function allocation process, a function analysis of the system's objectives is conducted. The result is a specification of functions, usually relative to each other against time.

Stage 1. Essentially, traditional questions of human and machine capabilities are asked. Allocations are made to human, computer, or a combination of the two based on a combination of eighteen criteria (shown in Table 7.1). These criteria reflect the traditional allocation dichotomy.

Stage 2. Allocations from stage 1 are further analyzed. Exclusively computer allocations are subjected to computer function analysis via systems engineering methods. Exclusively human and combined human/computer allocations are analyzed to determine what support can be provided to the human and what joint operations require an interaction between the human and computer. Joint operations are then examined to determine how the roles can be optimized.

In essence, then, we propose an iterative process in which the first stage highlights the relative strengths and weaknesses of humans and computers. The second stage uses the information from the first to focus and direct further analysis. Because the process is iterative, the allocations may change as new data or opportunities become clear. In the following, we describe how the first stage was applied in an information-system project. Methods for the second stage of the allocation process, task analysis and cognitive task analysis, can be found in, for instance, Beevis (1992), and Essens, Fallesen, McCann, Cannon-Bowers, and Dörfel (1994).

THE APPLICATION OF FUNCTION ALLOCATION IN ARDS/ADM

The two-stage process was developed at MacDonald Dettwiler and Associates (MDA) in interaction with the TNO Human Factors Research Institute and was applied to the systems development of the Advanced Development Model of an Artillery Regiment Defence System (ARDS/ADM).

Only after the start of the ARDS/ADM project did it become clear that focus on the human operator would be necessary for successful development of the system. MDA's project team recognized the need to ensure that the delivered system would be usable and acceptable in the field. In successful user-oriented design, the design process gives prime consideration to ensuring that the users' tasks are addressed as part of system development, rather than adhering strictly to a traditional engineering model that focuses on the hardware and software of the system itself.

The function allocation process presented here was developed in response to a variety of requirements. First, to be adopted successfully in industry, any analytical approach must be cost-effective. It must provide maximum utility at minimum cost. The ARDS/ADM project encompasses a large problem area that embodies a complex set of human tasks. An absolutely exhaustive function and task analysis was beyond the scope of the project and was a risk to be avoided. A feature of the function allocation process described here is that it discouraged overanalysis of the ARDS/ADM functions; that is, initial function allocation (stage 1) began with reasonably high-level functions specified. In instances where the stage 1 process suggested mixed allocation, the function was decomposed further. The process was repeated as necessary until the tasks and functions were defined sufficiently. Essentially, overspecification was reduced.

Second, as is common in the industry, few engineers on the ARDS/ADM project team had experience in structured function or task analysis. The iterative approach fostered an acceptable comfort level because the function allocation process was perceived as flexible.

Third, because the absolute judgements required by traditional function allocation methods are difficult to make, the new process used paired comparison judgements to perform allocation assignments. This

Table 7.1. Function allocation decision sheet

									Data Sensing						
Allocation to Human (H)	Proposed			Predefined[1]			Score		Monitors low-probability events.	Low absolute sensitivity thresholds.	Can detect masked signals.	Can acquire data incidental to task.	Not subject to jamming.	Good pattern recognition.	Sensitive to a variety of stimuli.
to Computer (C) Functions	C	H	Both	Regt	Mgt	Oth	C	H	Poor at unexpected events.	Higher thresholds.	Poor signal detection in noise.	Insensitive to extraneous factors.	Subject to disruption.	Little perceptual constancy.	Sensitive beyond human range.
1. Warning Phase															
Receipt of warning order.		√				√									
Anticipation of future operations.		√				√									
Conduct quick time estimate.		√					2	5	H	x	x	H	x	x	x
Conduct quick map estimate.		√					2	6	H	x	x	H	x	H	x
Get status of ammo.	√						8		C	x	x	C	x	x	x
Get enemy info.	√						8		C	x	x	C	x	x	x
Prepare warning order.	√						4	1	C	x	x	C	x	x	x
Issue warning order.	√						6	0	C	x	x	C	x	x	x
2. Main Planning Phase															
Receipt of orders from higher HQ.	√						3	0	C	x	x	C	x	x	x
Conduct time estimate.			√				3	4	C	x	x	H	x	x	x
Do an estimate.			√				3	4	H	x	x	H	x	x	x
Do an outline plan.	√						5	0	C	x	x	C	x	x	x
Issue outline plan to operations officer.	√						7		C	x	x	C	x	x	x
Recce to confirm plan [2]		√					1	7	H	x	H	H	x	x	x

Note: x = not relevant for this function

[1]Predefined by regiment or management, or for other reasons

[2]I.e., meet to verify that everything has been considered in the plan

Table 7.1. *(Cont.)*

	Data Processing							Data Transmission			
Allocation to Human (H)	Can choose alternate strategies.	Can generalize from limited data.	Computation weak and inaccurate.	Limited channel capacity.	Can store large amount of info. and recall relevant facts.	Can handle a variety of transient overloads.	Short-term memory poor.	Poor tracking.	Can adapt to situations.	Performance deteriorates with time.	High response latency.
to Computer (C)	Best for repeated strategies.	Deductive processes.	Accurate and rapid computation.	Channel capacity can be enlarged.	Can store and recall large amounts of info. quickly.	Overloads can seriously disrupt.	Short-term memory good.	Good tracking.	Cannot adapt to situations.	No fatigue, other time effects. Can do repeated tasks.	Can have low response latencies.
Functions											
1. Warning Phase											
Receipt of warning order.											
Anticipation of future operations.											
Conduct quick time estimate.	C	H	C	x	H	x	x	x	H	x	x
Conduct quick map estimate.	C	H	C	x	H	x	x	x	H	x	x
Get status of ammo.	C	C	C	x	C	x	x	x	x	C	C
Get enemy info.	C	C	C	x	C	x	x	x	x	C	C
Prepare warning order.	C	C	x	x	H	x	x	x	x	x	x
Issue warning order.	C	x	x	C	x	x	x	x	x	C	C
2. Main Planning Phase											
Receipt of orders from higher HQ.	x	x	x	x	x	x	C	x	x	x	x
Conduct time estimate.	C	H	C	x	H	x	C	x	x	x	x
Do an estimate.	C	H	C	x	H	x	C	x	x	x	x
Do an outline plan.	C	C	x	x	x	x	C	x	x	x	x
Issue outline plan to operations officer.	C	x	x	x	C	x	C	x	x	C	C
Recce to confirm plan 2)	H	H	x	x	H	x	C	x	H	x	x

shift in technique meant that domain experts (subject-matter experts) could learn to apply the process with minimal training, and the process was completed very quickly even for large numbers of functions.

Fourth, the traditional model (the split model, in Figure 7.1) was determined to be inadequate for ARDS/ADM software development. For ARDS/ADM development, the appropriate model of human-computer-process interactions was one in which the computer supports the human (the support model). The traditional approach did not take adequate account of the cognitive models and information processing that led to particular allocations, nor did the traditional approach focus design attention on how to support the user in the tasks allocated to the humans. In general, then, the process presented here provides more useful and appropriate analysis of the user's role as part of a complete system.

In addition to fostering an improved understanding of the mutually supportive roles of the human and the computer, the ease with which the process can be applied ensures proper and capable application. Simplicity is particularly important because many contractors do not have human factors specialists on staff. Some companies assign an engineering team member the responsibility for the human factors engineering aspects of a project. That party often does not have any training in human-related analysis. Accordingly, the method presented here was designed to be applied with little training.

Prior to applying the two-stage function allocation process described here, the functions are specified. (In ARDS/ADM development, the specification was done by an MDA human factors specialist and two expert artillery officers.) Identified functions are organized in a function allocation decision sheet format that allows easy comparison of each function against a set of allocation criteria. The function allocation decision sheet is comprised of a set of allocation criteria pairs developed from the seminal work of Fitts (1951, cited in Salvendy, 1987) and Bekey (1970) and is presented in Table 7.1. The allocation comparisons allow the domain expert to allot functions to humans or computers (or both) based on the capabilities of each. The comparisons address capabilities such as short-term memory, ready access to information, and inductive versus deductive reasoning. The comparisons describe inherent capabilities and so are independent of the hardware available, details of design, or implementation options.

In stage 1 of the function allocation process, one or more domain

experts review each specified function against each pair of criteria. (On the ARDS/ADM project, the primary domain expert was a trained artillery officer. A second domain expert, an MDA employee familiar with the domain, also completed part of the allocation process.) The allocation of the function on each of the criteria is then tallied. The resulting sum is examined to determine how many of the criteria favor human strengths and how many suggest computer implementation. At the completion of stage 1, each function is allocated to humans, machines, or a combination of both. The allocations are examined further in the second stage of the function allocation process.

When the function allocation tally from stage 1 points to a machine implementation, the designer takes into account the actual capabilities that led to the allocation of the function to the computer in the first place. For example, the function may require computation, a skill at which humans are notoriously weak. The appropriate implementation can then be addressed by the software design team.

If the allocation tally from stage 1 points to assignment to the human operator, then further decomposition helps determine any information that can help support the person to perform the tasks related to that function.

Any allocation that is at least partially assigned to the human operator is further examined to determine if machine support of that function is appropriate. Mixed allocations are decomposed to determine which functions should be allocated to the machine and which tasks to the human operator, and again human tasks are examined to see if computer support has potential benefits. Strictly machine functions are not analyzed further.

As expected, many functions in ARDS/ADM require the capabilities of both human and machines, because the command and control functions involve human decision making. Decomposition of these functions indicated which parts of the function should be assigned to machines and which to humans, and provided initial information that was used to determine how the human tasks could be supported. For example, the allocation of the function "Conduct quick time estimate" under the "Warning Phase" on the function allocation decision sheet (Table 7.1) indicates that repeating strategies and performing complex, rapid calculations are areas for support in a mainly human-operated function.

TRAINING AND INSTRUCTIONS

To achieve a valid function allocation analysis, the evaluator must be familiar with the domain. On ARDS/ADM, the primary domain expert was a trained artillery officer. A second domain expert, an engineer familiar with the domain, also conducted part of the function evaluation. After as little as 30 minutes of training, each domain expert was conversant enough with the process to continue without support.

As part of the training process, the evaluators walked through a number of the functions with a human factors specialist (the first author of the current paper). The eighteen comparisons were repeated for enough functions to allow the domain experts to feel comfortable with the process and their role. The domain experts were encouraged to make relatively quick decisions and were assured that their first impression is likely to be the most valid.

Not surprisingly, in many instances the analysis led to assignments that were counterintuitive to the domain experts. To prevent the domain experts from reevaluating the assignment in order to make it match expectations, the domain experts were assured that these discrepancies were valuable results of the process. Comfort with the process was also enhanced by assurance that the function allocations were not absolute, that the results of the analysis would be used to further understand the entire human/computer system rather than be applied as fixed answers.

CONCLUSIONS

A systematic allocation process is vital to optimizing automated support of any mission. The method presented here provides a generic tool that allows the designer to allocate functions to people or machines based on systematic consideration of computer/human capabilities. While function allocation can be done on an ad hoc basis—and often is—the process developed here enforces consideration of each function in terms of a specific set of factors, ensuring that all factors are considered and providing an objective basis for the decisions.

In addition, the process embodies a user-centered approach that forces consideration of the user as a part of the system. The model under which the approach was developed assumes that the interaction with the process is not statically divided between the human and computer. Rather, the human interacts with the process. To optimize that interac-

tion and ensure adequate support for the human, the results of an initial function allocation process are further reviewed to determine where and how the computer can best support the person. To do so, the designers must take into account human and computer strengths and weaknesses and the cognitive models of the user.

The results of a function allocation process provide a systematic basis for making judgements and an objective basis for design decisions. Also, the results point explicitly to those functions that need to be understood in more detail, while allowing the remainder to be addressed immediately.

Certainly, the method presented here and applied in the development of ARDS/ADM points to allocations that are counterintuitive both to the domain experts and to the design engineers. Equally important, the method focuses attention on the operator's tasks, missions, and cognitive models. Finally, the method is effective, efficient, and usable.

FURTHER DEVELOPMENT

To be most effective, this method should be applied early in the development of a software system. It is less effective to apply the results of a function analysis in a project that has already begun system design, data modelling, or software development. The functions should be defined and the allocation process begun in the first phase of the project.

Unfortunately, on the ARDS/ADM project, the analysis was delayed until after the project had begun and system design was well under way. While the process was useful and was beneficial to the development of the project, it would have had greater impact if it had been conducted much earlier. This would have provided much better understanding of the users' tasks in the initial system concepts and earlier focus by the design team on the human element of the ARDS/ADM system.

The process itself requires some modifications. To increase comfort levels of the domain experts, the instructions should include assurances that allocations that are counterintuitive provide valuable information. As well, assurance that the allocations will be examined in more detail increases the domain experts' confidence in their own decisions and allows them to complete the process more quickly and use their experience to make rapid decisions.

Domain experts rarely have experience in human factors analysis. Asking them to complete the function allocation decision sheet requires

some preparation, although it is not arduous or extensive. It is worthwhile to take a few minutes to prepare a detailed explanation of the meaning of each of the criteria. This guide should be targeted to users with little or no knowledge of human information processing or perception. It should be available to the domain expert for reference.

We caution that no one function allocation process is appropriate for all software system development. The process presented here is effective as an initial step. In many environments, it may be the only step. Its use does not preclude the application of other processes. Ideally, the results of this allocation method will form the basis for other processes. For example, using the output of this function allocation process as a base, prototypes can be built exploring various combinations of allocations and support structures to maximize effectiveness.

ACKNOWLEDGMENTS

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REFERENCES

Beevis, D. (Ed.). (1992). *Analysis techniques for man-machine systems design* (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

Bekey, G. A. (1970). The human operator in control systems. In K. B. DeGreen (Ed.), *System psychology*. New York, McGraw Hill.

Essens, P. J. M. D., Fallesen, J. J., McCann, C. A., Cannon-Bowers, J., & Dörfel, G. (1994). *COADE: A framework for cognitive analysis, design, and evaluation* (Report TNO-TM 1994 P-58). Soesterberg, The Netherlands: TNO Human Factors Research Institute. Also published as NATO Technical Report AC/243 (Panel 8) TR/17. Brussels: NATO Defence Research Group.

Fitts, P. M. (Ed.). (1951). *Human engineering for an effective air-navigation and traffic-control system.* Washington, DC: National Research Council.

Meister, D. (1985). *Behavioral analysis and measurement methods.* New York: Wiley.

Meister, D. (1991). *Psychology of system design.* Amsterdam: Elsevier.

Salvendy, G. (Ed.). (1987). *Handbook of human factors.* New York: Wiley.

Sheridan, T. B. (1987). Supervisory control. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 1243-1268). New York: Wiley.

Sheridan, T. B. (1988). Task allocation and supervisory control. In M. Helander (Ed.), *Handbook of human-computer interaction.* Amsterdam: Elsevier.

Woods, D. D., & Roth, E. M. (1988). Cognitive systems engineering. In M. Helander (Ed.), *Handbook of human-computer interaction.* Amsterdam: Elsevier.

8

TASK AND WORKLOAD ANALYSIS FOR ARMY COMMAND, CONTROL, COMMUNICATIONS, AND INTELLIGENCE (C^3I) SYSTEMS

B. G. Knapp

The emergence of highly automated information processing systems being developed by the US Army command, control, communications, and intelligence (C^3I) community raises certain questions related to the design of crews and interfaces for these systems. The US Army Research Laboratory (ARL) at Fort Huachuca, with expertise in information processing and behavioral science, has recently structured its research support to the C^3I community to develop systematic and quantitative methods for addressing these questions. This paper describes the approach taken in the development and application of job and workload assessment methods for new Army C^3I systems and the implications for function allocation. Methodologically, what was adopted was the measurement of C^3I task and job demands associated with new systems and new operating contexts, so that these demands could be compared to current performance baselines. Critical parameters for comparison are the demands placed on soldiers due to new job factors and mission conditions, and soldiers' knowledge, skills, and abilities. A series of six steps in the method for C^3I task and workload analysis are described and illustrated using two case studies.

INTRODUCTION

The US Army continuously reviews its missions, develops new tactics and plans, and acquires new equipment in order to fulfil its modern de-

fense roles. A critical issue for Army decision makers is ensuring that soldiers, as currently selected and trained, are capable of operating the new equipment and performing effectively. In particular, the emergence of highly automated information-processing systems being developed by the Army command, control, communications, and intelligence (C^3I) community raises certain questions: How well do the capabilities of current Army personnel match the demands and designs of the high-technology, supervisory control systems being developed? Do the new systems differ incrementally or exponentially in workload from immediately preceding systems? What are the tactical operating procedures and training implications of introducing the new automation components?

The US Army Research Laboratory (ARL) at Fort Huachuca, with expertise in information processing and behavioral science, has recently structured its research support to the C^3I community to develop systematic and quantitative methods for addressing these questions. Efforts have been targeted at assessing task performance during C^3I system design stages, prior to final testing, to ensure that functions and tasks are optimally distributed among soldiers and automated processors, and that information-processing workload does not exceed resource capabilities. This paper describes the approach taken in the development and application of job and workload assessment methods for new Army C^3I systems and the implications for function allocation.

DEVELOPMENT OF THE METHOD

The methods being developed by ARL are designed to assess the impact of mission, task, personnel, and environmental variables (e.g., new equipment, expanding scope of tactical missions, increased battlefield tempo, new operating tactics, changing personnel characteristics in an all-volunteer Army, etc.) on C^3I soldier performance by augmenting or supplanting conventional task analysis and workload estimation techniques. Conventional methods have been adequate for the procedure-oriented, perceptual-motor tasks characteristic of aviation, maneuver, and weapon control systems, but they are not sufficient to address the process-oriented, cognitive tasks central to C^3I systems. It was clear that function allocation for C^3I systems must be supported by a more comprehensive and elaborate task and workload definition and analysis process, allowing collection of data that can be used persuasively in

deciding among alternative soldier and machine function allocation designs.

Methodologically, what was adopted was the measurement of C^3I task and job *demands* associated with new systems and new operating contexts, so that these demands could be compared to current performance baselines. Critical parameters for comparison are the demands placed on soldiers due to new job factors and mission conditions, and soldiers' knowledge, skills, and abilities.

This approach departs from conventional task decomposition and time studies that rely on time per task and additive network models to detect work overload. Instead, information-processing tasks are measured not so much in terms of *time spent* but in terms of *resources* used to produce information products (situation report, battle plan, operations order, etc.). A strong case can be made that increased cognitive demands, along with a decrease in time available for information processing, will cause information output products to be compromised. Add to this any degradations in environmental and communications factors, and the allocation of functions between humans and automation becomes critical.

STEPS IN THE METHOD

Task and workload analysis for C^3I missions based on resource demands involves the series of steps described below:

- *Step 1: State issues and objectives of analysis to focus on methods needed.* Depending on the questions being raised, this allows data collection to be targeted to exactly what is needed. For example, is allocation of soldier functions related to declining personnel inventories, design of training plans, need for equipment specifications, or a combination of factors?
- *Step 2: Derive mission-event flow and anticipated scenario sequences.* Sessions with subject matter-experts must proceed beyond eliciting traditional task lists to depicting graphical representations of task and work flows triggered by scenario and information events. This allows subsequent analysis to account for task loops, decision points, and communication lines (person and machine). An example of a simple task flow diagram is shown in Figure 8.1.

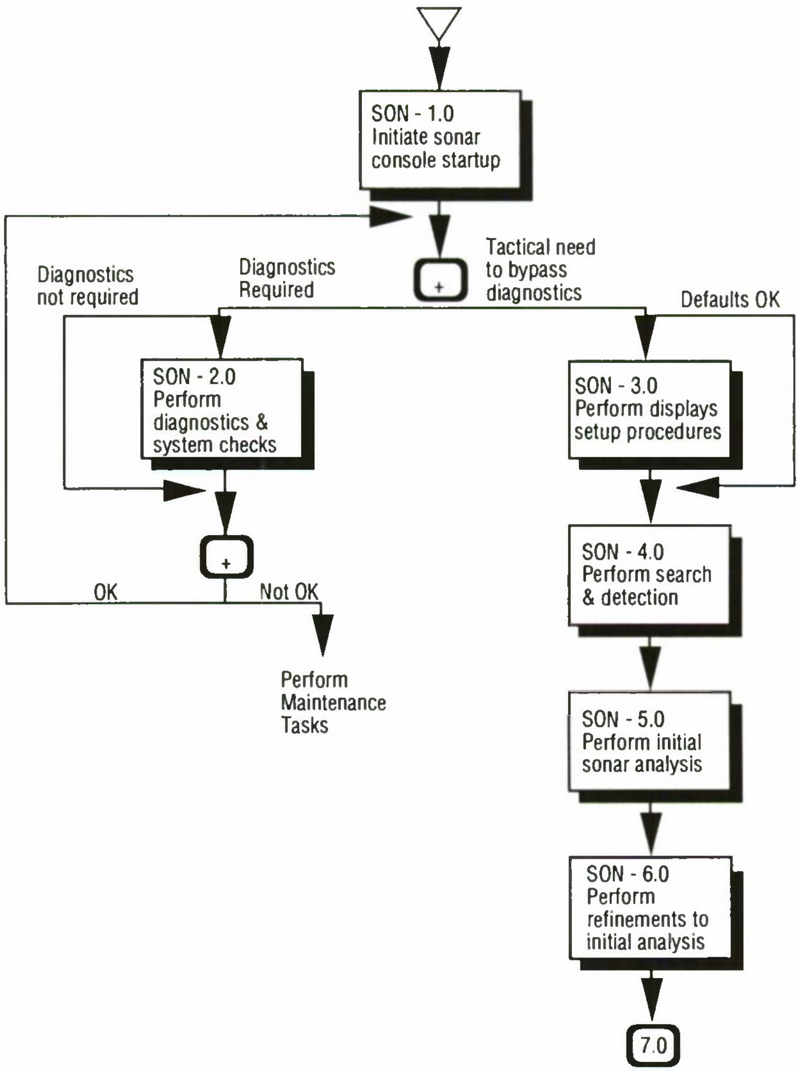

Figure 8.1. Sample task flow diagram.

- *Step 3: Conduct assessment of cognitive functions and tasks within the work flow* by measuring relevant task and environmental characteristics (e.g., attributes of incoming information, work environment design, ambient conditions, mission conditions, etc.) and soldier resources (performance capabilities, knowledge, skills, abilities, and limits). This extends steps 1 and 2 by selecting for measurement the variables pertinent to the job within the context of the issues. A sample listing of potential job variables from which such selections could be made is shown in Table 8.1.

- *Step 4: Identify potential information inputs and decision-action outputs.* Incoming information is the stimulus to action (task performance), and outgoing information products result from data transformation and analysis tasks that produce operator decisions and actions. This step provides initial insight into how the work could be distributed among crew members and machine processors, since various diagrams, variable listings, and preliminary values form a picture of the job situation.

- *Step 5: Assess workload by formally measuring task demands, under different mission conditions, soldier capabilities, and environmental variables.* Depending on the issue, task demand is measured on one or a combination of variables. Measures are drawn from existing human performance databases or from data collected from experts using available or custom-designed measurement instruments.

- *Step 6: Construct integrated task and workload models.* A "model" of the C^3I tasks and associated workload for a given job may be as simple as a paper-and-pencil tally and comparison of the measures on a few variables. Or it may involve a complex network representation of tasks, task interrelationships, and workload parameter values for the tasks that requires a more sophisticated, computer-based analysis. In either case, workload profiles are developed and compared to derive the impacts of important factors affecting task performance.

Table 8.1. Example of job variables for workload assessment

1.0 Operational Environment

Scenario Pece (threet complexity - # entities, time pressure,
scope of mission) Operetionel Mode (plan or execute)
Tactic Mode (offenses or defense)

2.0 System Environment

Autometion Level (manual, Auto 1, Auto 2, Auto 3)
System I/O Complexity (high, medium, low)
Required Protocols (difficult, moderate, easy)

3.0 Incoming Information end Detebase Environment

Form (text, voice, fece-to-fece, mep grephics, imegery)
Source (commander, staff, subordinate, flenk unit, higher
authority) Content (orders, guidance, status, situation report,
system elerts) Rete (frequency of incomings by type)

4.0 Linking Demands

Interection-Autonomy Level (high, moderate, low)
Input-Output Chennels (number end type)
Network Complexity (meny links and nodes, moderete, few)

5.0 Cognitive Processing Stete

A. Information Acquisition (complex, moderate, nearly automatic)
B. Informetion Trensmission (complex, moderete, routine)
C. Date Manipulation (complex, moderete, simplistic)
D. Wargaming (prediction-inference, analysis, option generation)

6.0 Workspece Attributes

Soldier Machine Interfece (user-unfriendly, mixed, user-friendly)
Ambient Conditions (extreme, moderate, just right)

7.0 Group Integrity

Mobility Stete (stationery-all together, stationary-distributed,
mobile-stationary mix, all mobile) Information Exchange Capability
(face-to-fece, voice, digitel) Cluster Configuration (functional area,
matrix, novel)

8.0 Personnel Status

Skill Mix (experienced, experienced-inexperienced mix,
inexperienced) Composition (technical, enalytical, supervisory)
Shift Protocol (all dedicated, trade-offs)
Numbers Per Cell

APPLICATION OF THE METHOD: TWO CASE STUDIES

ARMY AIRCREW REQUIREMENTS FOR JSTARS

Step 1

Of immediate interest for certain Army intelligence systems is the assessment and comparison of skill and ability requirements needed for tasks by prospective soldiers. For the Joint Surveillance/Target Acquisition Radar System (JSTARS), a new high-technology intelligence sensor system designed to provide real-time imagery information on the tactical battlefield, a question arose regarding the suitability of current personnel for performing job tasks on both the prototype and the objective system. At issue was whether imagery operators would be overloaded by the proposed capabilities of the objective system. The initial job was performed by two imagery operators using a limited, prototype version of JSTARS in Operation Desert Storm (the 1991 Gulf War). The objective system could accommodate three operators, if needed.

Step 2

The JSTARS job flow was obtained from JSTARS experts: those familiar with functions performed in predecessor and prototype systems, and those designing the objective JSTARS. The functional job flow is shown in Figure 8.2. Six functions were identified: mission planning, brief, preflight, outbound flight, on-station mission performance, and post-mission duties and debrief. Of greatest interest for demand assessment was the on-station mission function. A further decomposition of this function is shown in Figure 8.3.

Step 3

To compare cognitive task demand on the JSTARS prototype and objective JSTARS, a job assessment method that included cognitive skills and abilities was required. Taxonomies that incorporate knowledge, skills, and abilities for many jobs exist in the literature (Muckler, Seven, & Akman, 1990a), and an *evaluation* taxonomy was developed

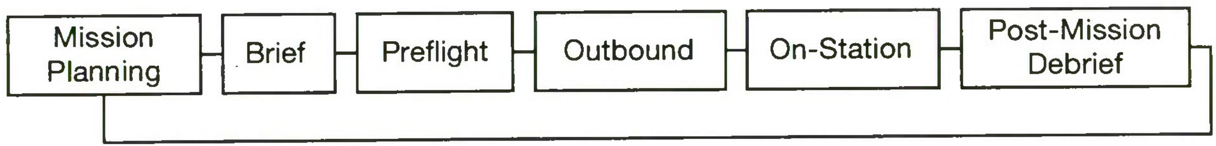

Figure 8.2. Functional job flow for Joint Surveillance/Target Acquisition Radar System (JSTARS).

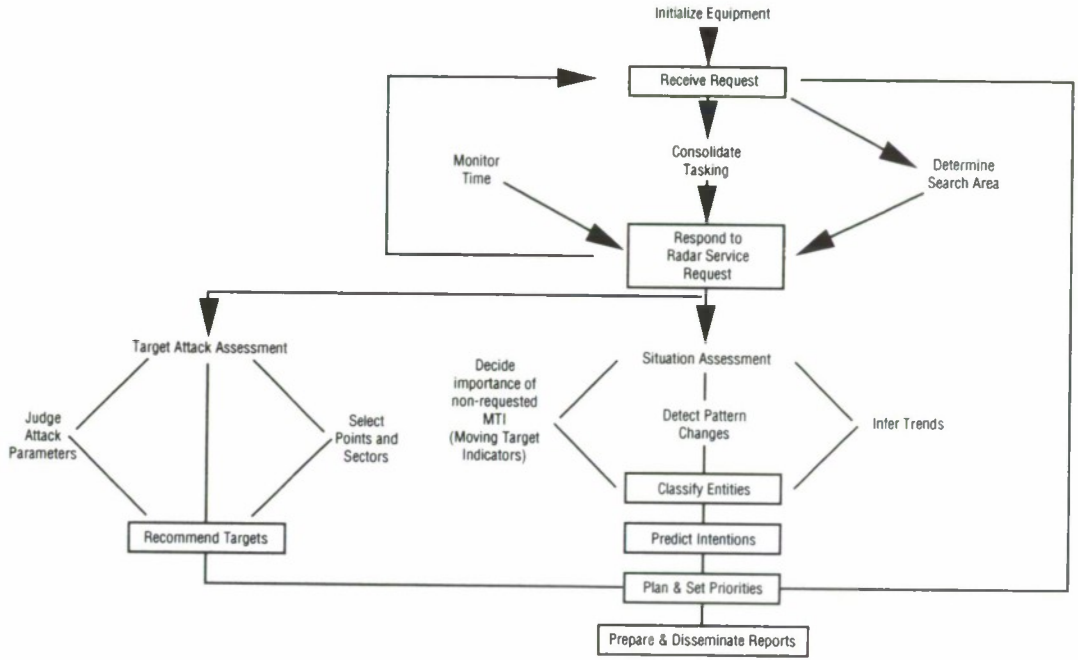

Figure 8.3. JSTARS functional flow decomposition of the on-station mission operations function.

specifically for C^3I jobs. The evaluation taxonomy provided the hierarchy of variables specific to the job domain and is used to structure evaluations and point to measurement methods.

The evaluation taxonomy (Muckler, Seven, & Akman, 1990b) is shown in Figure 8.4. For the soldier skills and abilities questions raised for JSTARS, variables in the taxonomy were selected from the "Soldier

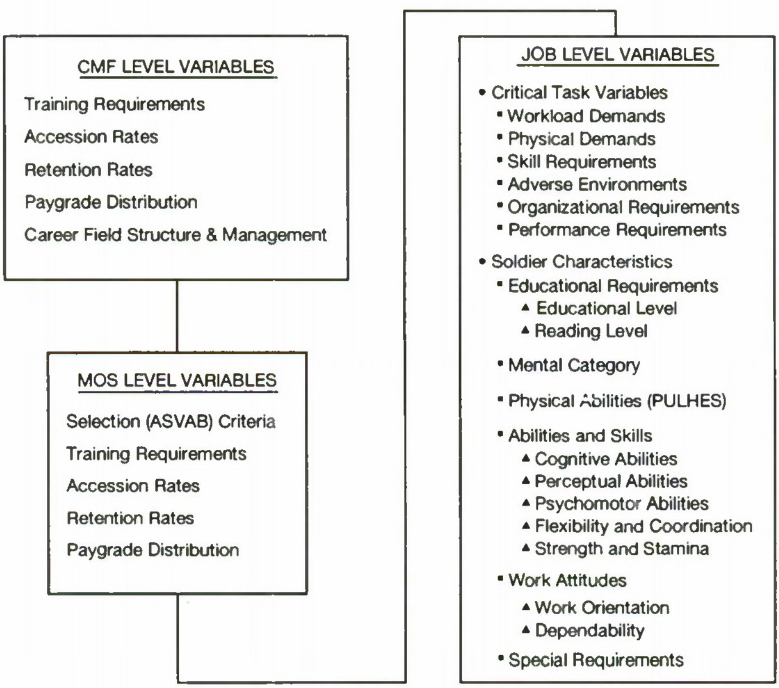

Figure 8.4. Command, control, communications, and intelligence (C^3I) occupational specialty evaluation taxonomy. CMF = Career Management Field; MOS = Military Occupational Structure; ASVAB = Armed Services Vocational Aptitude Battery; PULHES = classification of physical abilities in terms of six factors: P (physical capacity or stamina), U (upper extremities), L (lower extremities), H (hearing and ears), E (eyes), S (psychiatric). Each MOS has a PULHES profile detailing job requirements.

Table 8.2. Modified skills and abilities taxonomy based on Fleishman and Quaintance (1984)

COGNITIVE SKILL & EXPERIENCE CLUSTERS		PERCEPTUAL-MOTOR ABILITY CLUSTERS	
COMMUNICATION	CONCEPTUAL	VISION	AUDITION
1. Oral Comprehension	5. Memorization	24. Near Vision	31. General Hearing
2. Written Comprehension	6. Problem Sensitivity	25. Far Vision	32. Auditory Attention
3. Oral Expression	7. Originality	26. Night Vision	33. Sound Localization
4. Written Expression	8. Fluency of Ideas	27. Visual Color Discrimination	
	9. Flexibility of Closure	28. Peripheral Vision	
	10. Selective Attention	29. Depth Perception	
	11. Spatial Orientation	30. Glare Sensitivity	
	12. Visualization		
REASONING	SPEED-LOADED	PSYCHOMOTOR	GROSS MOTOR
13. Inductive Reasoning	19. Time Sharing	34. Control Precision	41. Extent Flexibility
14. Category Flexibility	20. Speed of Closure	35. Rate Control	42. Dynamic Flexibility
15. Deductive Reasoning	21. Perceptual Speed & Accuracy	36. Wrist-Finger Speed	43. Speed of Limb Movement
16. Information Ordering	22. Reaction Time	37. Finger Dexterity	44. Gross Body Equilibrium
17. Mathematical Reasoning	23. Choice Reaction Time	38. Manual Dexterity	45. Gross Body Coordination
18. Number Facility		39. Arm-Hand Steadiness	46. Static Strength
		40. Multilimb Coordination	47. Explosive Strength
			48. Dynamic Strength
			49. Trunk Strength
			50. Stamina
GREATER SKILL & EXPERIENCE RESULT FROM EXTENSIVE TRAINING & JOB EXPOSURE		HIGHER LEVELS OF ABILITIES ARE A FUNCTION OF INNATE CAPABILITIES & LOW-LEVEL PRACTICE DRILLS	

characteristics: Abilities and skills" category. These were decomposed to establish a core list of abilities and skills to be measured. The listing selected as most relevant to C^3I, well-defined and empirically based, was drawn from the work of Fleishman and Quaintance (1984) and is shown in Table 8.2 (extensive discussion on the rationale for this selection is found in Muckler et al., 1990a).

Modifications to the Fleishman work involved clustering skills and abilities according to higher-level logical aggregates to address questions and obtain measures at different levels of detail. The taxonomy shown in Figure 8.5 is organized by the skill and ability clusters that were devised.

The abilities and skills taxonomy led to the design and development of a flow diagram and scaling measurement method, the *Job Comparison and Analysis Tool* (JCAT). This tool is based on a technique originally used by Mallamad, Levine, and Fleishman (1980), but also included a matrix of job functions to further isolate skill and ability demands.

Steps 4, 5, and 6

Steps 4, 5, and 6 for task and workload assessment were combined for the JSTARS case study.

In this single-system study, one information input condition was assumed (step 4), in which operators are triggered to conduct the entire mission, defined as a "typical JSTARS targeting and surveillance mission for a corps sector." Cognitive demands were assessed (step 5) using the JCAT instrument with the JSTARS functions. Other potential loading factors (environment, information conditions, group dynamics, etc.; see Table 8.1) were held constant, and the essential factor for increased loading on JSTARS operators was the introduction of the new equipment. Thus, the model of tasks and subsequent workload (step 6) is a set of quantitative profiles of the mission functions under two conditions, prototype JSTARS and objective JSTARS, which discriminate job demands for two and three operator positions.

Study Execution and Results

The JCAT instrument was used to select and scale ability and skill requirements for the JSTARS prototype and the objective system.

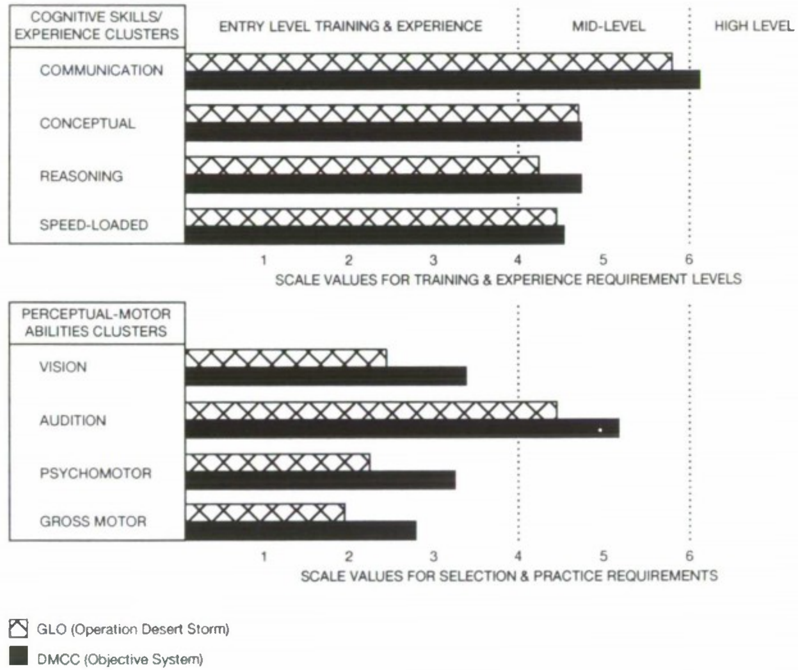

Figure. 8.5. Strip chart of JSTARS job demands from Job Comparison and Analysis Tool (JCAT) data table. GLO - Ground Liaison Officer (prototype system); DMCC - Deputy Mission Crew Commander (objective system).

Table 8.3. JCAT demand matrix for JSTARS Army aircrew positions

	POSITION				
COGNITIVE SKILL & EXPERIENCE CLUSTERS (TRAINING-EXPERIENCE)	GLO Operation Desert Storm	DMCC Objective System	AST Operation Desert Storm	AST/TSS Objective System	ARSM/STO Objective System
COMMUNICATION (4) *	5.83**	6.12	4.66	5.25	3.62
CONCEPTUAL (8)	4.66	4.68	4.91	4.87	4.95
REASONING (6)	4.19	4.66	5.16	4.91	4.72
SPEED-LOADED (5)	4.43	4.50	4.26	5.10	4.70
PERCEPTUAL MOTOR ABILITY CLUSTERS (SELECTION & PRACTICE)					
VISION (7)	2.38	3.35	3.04	4.00	3.04
AUDITION (3)	4.44	5.16	4.33	5.16	4.44
PSYCHOMOTOR (7)	2.19	3.14	2.85	4.00	2.57
GROSS MOTOR (10)	1.86	2.75	1.83	2.85	1.90

* NUMBERS IN PARENTHESES REFER TO NUMBERS OF SKILLS OR ABILITIES IN EACH CLUSTER.
** NUMBERS IN EACH CELL REPRESENT THE AVERAGE OF RATINGS ON AN 0-7 SCALE.

SKILL/EXPERIENCE LEVELS
0-4 ENTRY-LEVEL
4-6 MID-LEVEL
6-7 HIGH-LEVEL

ABILITY LEVELS
0-4 LOW
4-6 MEDIUM
6-7 HIGH

GLO - Ground Liaison Officer
DMCC - Deputy Mission Crew Commander
AST - Aerial Surveillance Technician
TSS - Target Surveillance Supervisor
ARSM - Army Radar Systems Manager
STO - Search/Track Operator

JCAT elicits judgements of ability and skill demands using behaviorally anchored scales along with a matrix of the six job functions (Figure 8.2).

JCAT was administered to six subject-matter experts for each job, and profiles of job task demands for each version of JSTARS were computed. Comparative analyses were then performed to determine the impact of any profile mismatches.

Table 8.3 shows sample results from the JSTARS JCAT profiles. Numerical values in the matrix indicate demand level (high, medium, low) for the skill and ability clusters for operator positions in each system. (Ranges are taken from the behavioral anchors validated in previous research.) For the GLO (ground liaison operator) position, communication skills present the highest demand (5.83) for the prototype system. In the objective system (for which the job position title was changed to DMCC, deputy mission crew commander), communication demand increases (6.12). The tabular data for the GLO-DMCC comparison are shown in the strip chart display in Figure 8.5.

Using the high-demand skill and ability clusters identified in the profiles, JCAT data were further analyzed to determine the source of loading from two aspects: the underlying skill(s) or ability(s) within the cluster(s) responsible for high demand, and the function and task area(s) where the high demand was indicated. Tables 8.4 and 8.5 show the data for GLO-DMCC comparisons. Together these data form a picture or *profile* of the job and indicate that only moderate to highly experienced operators should be considered—not entry level personnel for the aircrew (detailed discussion and full data tables for the JSTARS positions are found in Knapp, 1994). The communications, conceptual, reasoning, speed-loaded, and auditory clusters are key to workload and must be considered in selecting and training these operators.

In general, most requirements for the objective system exceeded those for the prototype, so workload is best absorbed by a third operator (or additional automation) for future missions. The increase involves communications skills and auditory ability for over half of the mission functions (planning, briefing, on-station, debriefing), while increased cognitive demands (time sharing, inductive and deductive reasoning, problem sensitivity, etc.) are evident mostly during the on-station mission operations. For this reason, automation as a design alternative may be difficult. Off-loading of communications and auditory functions is better addressed by increasing personnel proficiency and ensuring that

Table 8.4. Skill and ability demands by JSTARS mission function

SKILL/ABILITY CLUSTER	MISSION PLANNING		BRIEF		PREFLIGHT		OUTBOUND		ON-STATION		POST MISSION DEBRIEF/ OFF-STATION	
	GLO	DMCC	GLO	DMCC	GLO	DMCC	GLO	OMCC	GLO	OMCC	GLO	DMCC
Communication	4.04	5.87	5.37	5.87	3.66	4.12	3.58	4.12	4.95	5.00	5.37	5.87
Conceptual	3.60	3.94	2.51	3.56	2.37	2.88	2.99	3.31	4.37	4.62	3.72	3.69
Reasoning	3.60	4.67	2.44	3.58	1.44	2.25	1.60	2.50	4.03	4.50	3.89	4.41
Speed-Loaded	2.86	3.60	1.99	2.80	2.46	3.70	2.86	3.90	4.43	4.50	1.99	2.90
Visual	2.04	2.79	1.94	2.86	2.09	3.07	2.09	3.07	2.28	3.14	2.04	3.14
Auditory	2.66	3.33	2.66	3.00	3.88	4.50	3.99	4.83	4.44	5.17	2.66	3.00
Psychomotor	1.33	1.93	1.28	1.86	2.19	3.14	2.19	3.14	2.19	3.14	1.52	2.29
Gross Motor	1.09	1.60	1.09	1.60	1.66	2.45	1.76	2.60	1.86	2.75	1.50	2.00

Performance Oemand Levels: 0-4 Low 4-6 Medium 6-7 High

GLO - Ground Liaison Officer; DMCC - Deputy Mission Crew Commander

Table 8.5. Decomposition of critical JCAT clusters for JSTARS deputy mission crew commander (DMCC)

CLUSTER	SKILL/ABILITY ELEMENT	(AVERAGE DEMAND LEVEL, 0-7 SCALE)
Auditory	* Auditory Attention	(4.75)
	* General Hearing	(4.58)
	Sound Localization	
Communication	* Oral Comprehension	(5.58)
	* Oral Expression	(5.16)
	* Written Expression	(5.00)
	* Written Comprehension	(4.83)
Conceptual	* Originality	(4.50)
	* Problem Sensitivity	(4.41)
	* Memorization	(4.50)
	Selective Attention/Visualization	
	Flexibility of Closure	
	Fluency of Ideas	
	Spatial Orientation	
Reasoning	* Inductive	(4.75)
	* Deductive	(4.25)
	* Information Ordering	(4.08)
	Category Flexibility	
	Mathematical Reasoning	
	Number Facility	
Speed-Loaded	* Speed of Closure	(4.33)
	* Time Sharing	(4.08)
	Perceptual Speed & Accuracy	
	Reaction Time	
	Choice Reaction Time	

other nondemanding mission functions (preflight duties, aviation-specific duties) are handled by other aircrew personnel.

TASK AND WORKLOAD DEMANDS FOR ARMY COMMAND AND CONTROL STAFF

A more comprehensive task and workload analysis using the six steps detailed above is currently under way. The objective is to evaluate whether soldiers in an Army command and control (C^2) staff, which supports brigade and division commanders, can perform adequately with proposed new automation tools during on-the-move operations and in distributed communications environments. Command staff support groups are now set to be replaced by smaller, more mobile support teams who will share and analyze digitized information more autonomously, rather than hovering over a shared map board and routinely conversing in person.

The variables of Table 8.1, encompassing a range of mission conditions, information conditions, personnel, and environmental conditions, are being assessed using a combination of new measurement and modelling techniques. The goal is to quantify the impact of all variables listed, singularly and in combination, and to differentiate the command staff job demands in current and proposed tactical environments. The analysis has begun with the development of a work flow model, shown in Figure 8.6. An underlying assumption is that, regardless of job conditions (new technology, increased battlefield tempo, configuration of C^2 staff personnel, etc.), the staff functions to be performed are invariant and consist of a basic functional flow of information input tasks (acknowledge data, compare to "picture"), information-processing tasks (estimate impact of new data, recommend changes to plans and orders, etc.), and output tasks (adjust plans, issue orders and directives).

What defines the workload is the nature and pace of information within the work flow, the working conditions, and personnel capabilities and dynamics. Incoming information is the trigger to processing and action, and information events account for demand on operator resources. In a simplistic example, Figure 8.7 shows one information event, "Firing battery down" (incoming data to a fire support element staff operator that an outlying firing battery is out), and how this event triggers a series of tasks and skill requirements at varying levels

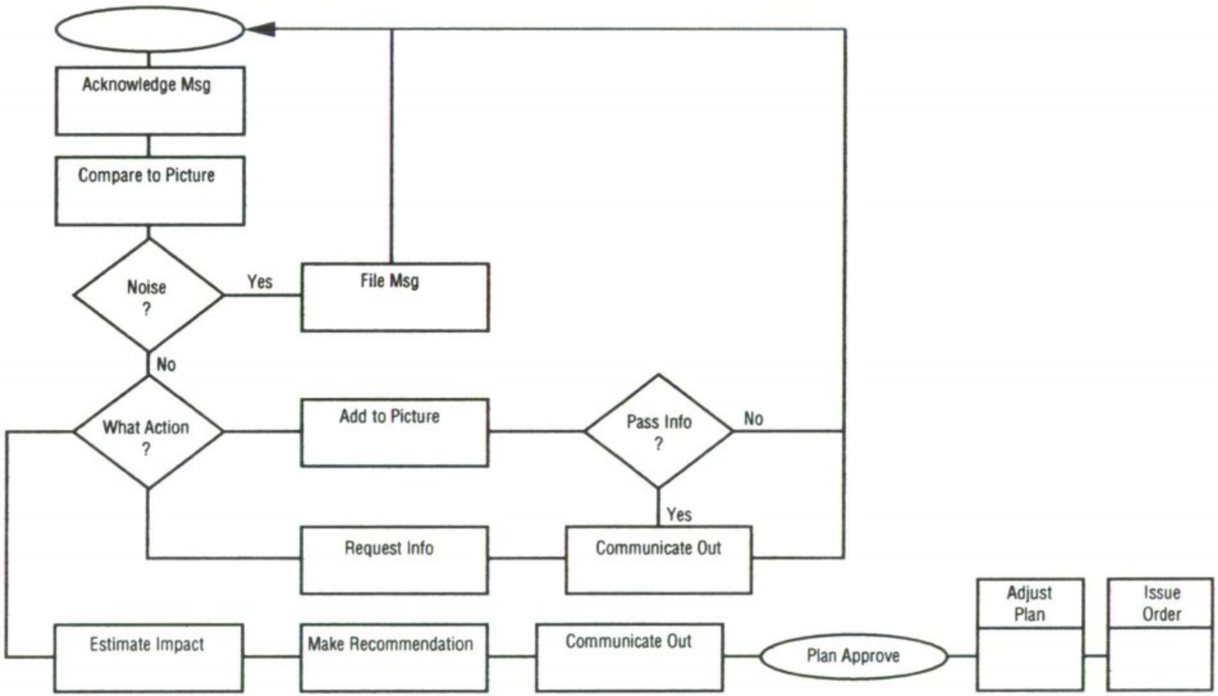

Figure 8.6. Generic work flow for Army command and control (C^2) staff.

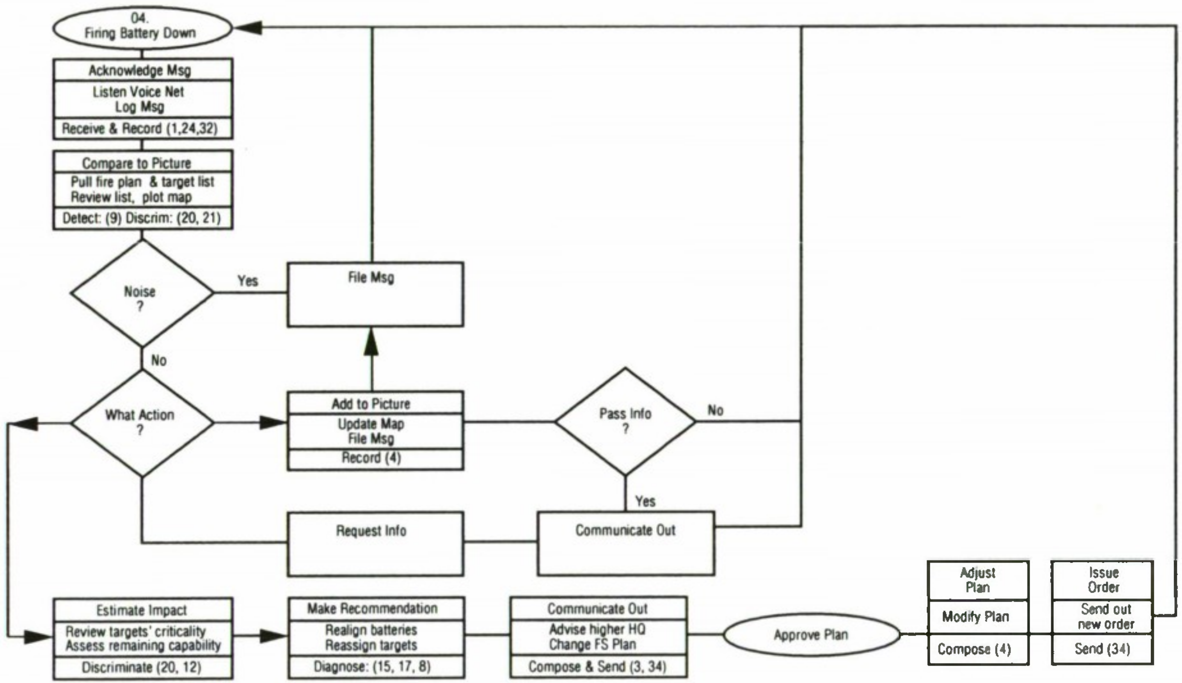

Figure 8.7. Work flow for fire support staff triggered by information even 04., "Firing battery down." Numbers in parentheses refer to skills and abilities list of Table 8.2.

of processing complexity. For example, the "Compare to picture" task involves detection and discrimination skills, including visualization and speed of closure (refer to the skills and abilities listing in Table 8.2).

The next step in workload estimation for this single information event is to assign demand estimates for the skills triggered. Separate information events within and between staff sections could be compared at this point to get a rough estimation of differing workload; however, a more operationally realistic picture of the mission is obtained using additional parameter values for sequential and concurrent information events, different information event rates, and environmental, automation technology, and group dynamics variables listed in Table 8.1. This results in a *library* of C^2 mission profiles, which can be executed in a task *network and resource demand* computational model or models (e.g., ARL's CREWCUT, 1993).

To determine the parameter values to populate the mission profiles, detailed data must be elicited from C^2 experts on the current and expected distribution of information event types and rates, and on the characteristics of the automation technology proposed. Research will be required to develop and assign scale values for the personnel and environmental variables, such as the knowledge, skill, and abilities demands for each mission and staff section. Model runs then produce output reports that show points of overload in task demands under different variable conditions. These are the data from which the function allocation decisions will be made.

SUMMARY

Function allocation decisions for C^3I systems depend on sound task and workload analysis to provide quantitative profiles of the jobs being designed. Since the tasks in these systems are mainly cognitive in nature and are linked to control of automated systems, a systematic approach to the analysis and measurement of job demand is essential. The work presented in this paper has illustrated one such method being used for new Army C^3I systems, which shows considerable success in meeting the challenge of measuring and evaluating the information-processing tasks characteristic of these systems.

REFERENCES

Fleishman, E. A., & Quaintance, M. K. (1984). *Taxonomies of human performance: The description of human tasks.* Orlando, FL: Academic Press.

Knapp, B. G. (1994). *Preliminary analysis of army aircrew requirements for joint STARS: Human performance requirements and job demands* (ARL-MR-178 Report). Fort Huachuca, AZ: US Army Research Laboratory.

Little, R., Dahl, S., Plott, B., Wickens, C., Powers, J., Tillman, B., Davilla, D., & Hutchins, C. (1993). *Crew reduction in armored vehicles ergonomic study (CRAVES)* (ARL-CR-80). Fort Huachuca, AZ: US Army Research Laboratory.

Mallamad, S. M., Levine, J. M., & Fleishman, E. A. (1980). Identifying ability requirements by decision flow diagrams. *Human Factors,* 22(1), 57-68.

Muckler, F. A., Seven, S., & Akman, A. (1990a). *Proposed method for military intelligence job ability assessment* (ARI Research Note 90-135). Alexandria, VA: US Army Research Institute.

Muckler, F. A., Seven, S., & Akman, A. (1990b). *Construction of military intelligence military occupational specialty taxonomy* (ARI Research Note 91-10). Alexandria, VA: US Army Research Institute.

9

ADAPTIVE FUNCTION ALLOCATION FOR SITUATION ASSESSMENT AND ACTION PLANNING IN C^3 SYSTEMS

W. Berheide, H. Distelmaier, and B. Döring

Improvements in sensor and effector technologies in modern command, control, and communication (C^3) systems increase the amount and complexity of information to be processed and greatly decrease the time available to process that information. Supporting the operators of these systems by means of intelligent and adaptive human-machine interfaces can at least partly handle this situation. This approach requires a situation-specific allocation of functions between operator and machine system components. This paper starts with a general description of human tasks in military decision situations. Principles for supporting human decision making in C^3 systems are presented. The support concept of a knowledge-based user assistant that comprises a dialogue monitor, a situation monitor, an action planner, and a display manager is explained in detail. An object-oriented implementation and prototyping of the assistant based on a hierarchical function analysis is explained; tasks of the principle warfare officer in a Navy combat information center are used as an example.

INTRODUCTION

Improvements in sensor and effector technology in modern command, control, and communication (C^3) systems increase the amount and complexity of information to be processed and greatly decrease the time available to treat this information. This situation can be handled partly by increasing processing speed through a higher degree of automation. But human decision makers cannot be replaced in military systems. In

unforeseen and emergency situations in complex military environments, a higher degree of automation leads to reduced decision time and increased information complexity, which results in an intolerable workload level for human operators and decision makers. The consequence is increased human errors and reduced overall system performance. Supporting the operators (users) through intelligent and adaptive human-machine interfaces can help reduce these problems. This approach requires situation-specific allocation of functions between system users and machine system components.

Information-processing functions normally performed in C^3 systems are situation assessment, action planning, action command, and checking of action accomplishment. These functions describe the course of action in military decision situations. Viewing such situations from a behavioral perspective, Wohl (1981) identified generic elements that describe the military decision-making process and constitute the basis of his SHOR model. These elements are: stimulus, hypothesis, option, and response (Figure 9.1).

The stimulus element includes data collection, correlation aggregation, and recall activities. In a tactical air-threat situation on a ship, such data are, for example, distance, bearing, and speed of a target, and sensor and weapon range of own ship. Often those data are available only sequentially over time, and the operator must store them in memory. On the basis of the collected information, the decision maker creates a hypothesis concerning the actual threat situation. When new data are received, for example, new target data such as its classification and sensor and weapon range, the evaluation of the initial hypothesis results in its confirmation or rejection. In the latter case, a new hypothesis will be generated considering the newly available data. Often, due to the uncertainty of data, hypotheses can be generated only with certain probabilities. Then, one hypothesis must be selected as the most likely cause of the data. For each hypothesis, the decision maker must generate and evaluate alternative options for solving the problem. The evaluation has to consider option effectiveness with regard to mission accomplishment and system safety. The most appropriate option is selected. On the basis of the selected option, the decision maker takes action that includes planning, organizing, and executing the response to the problem situation.

When accomplishing these decision-making functions, the human decision maker has to deal with two types of uncertainty (Wohl, 1981):

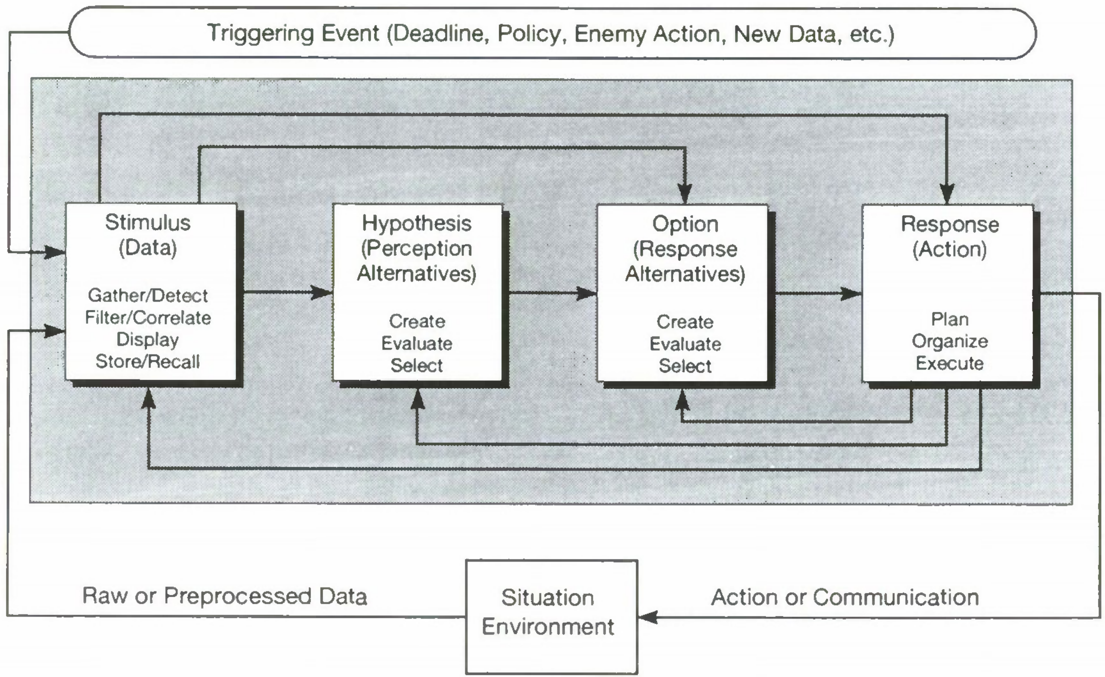

Figure 9.1. Elements and functions of the military decision process. From "Force management decision requirements for air force tactical command and control," by J. G. Wohl, 1981, *IEEE Transactions on Systems, Man, and Cybernetics, 11*(9), p. 626, Fig. 8. Copyright © 1981 IEEE. Reprinted with permission.

(1) information input uncertainty, which creates the need for hypothesis generation and evaluation; and (2) consequence-of-action uncertainty, which creates the need for option generation and evaluation. Generally, a human decision maker has specific deficiencies in performing these elementary functions due to human capabilities and limitations (Anderson, 1988; Wickens, 1984). Edwards (1990) points out that such deficiencies are especially likely in pilot performance. Comprehensive deficiency listings have been compiled for the design of decision support systems (Cohen, Thompson, & Chinnis, 1985; Sage, 1991). Only some examples will be given here.

In performing the function "Gather data," for example, human decision makers tend to use only easily available data; they consider only a few samples of data. In performing the functions "Create and evaluate hypothesis," they are likely to ignore data that disconfirm the hypothesis currently being considered, tend to generate recently used hypotheses over again, and have difficulty assessing probabilities. In performing the functions "Create, evaluate, and select option," humans segment complex options into "natural" components and treat the elements as if they were independent choices, which leads to suboptimal portfolios. They have difficulty recalling all situation-relevant options and under time pressure tend to give more weight to negative evidence concerning alternatives than to positive evidence.

CONCEPT FOR SUPPORTING HUMAN DECISION MAKING

To overcome the deficiencies mentioned above and to support the human operator in decision making in complex systems, adaptive aiding concepts have been developed (Rouse, Geddes, & Curry, 1988; Rouse, 1991). In recent years, these concepts have been applied mainly in support for aircraft pilots (Amalberti & Deblon, 1992; Banks & Lizza, 1991; Dudek, 1990; Rouse, Geddes, & Hammer, 1990; Wittig & Onken, 1992). Basic to these concepts is the philosophy that total automation cannot be the utmost objective of system development. The consequence of this philosophy is that the role of the operator as decision maker has to be accepted prior to system design. This is important because the overall performance of complex systems depends heavily on human performance, particularly when abnormal and emergency situations arise.

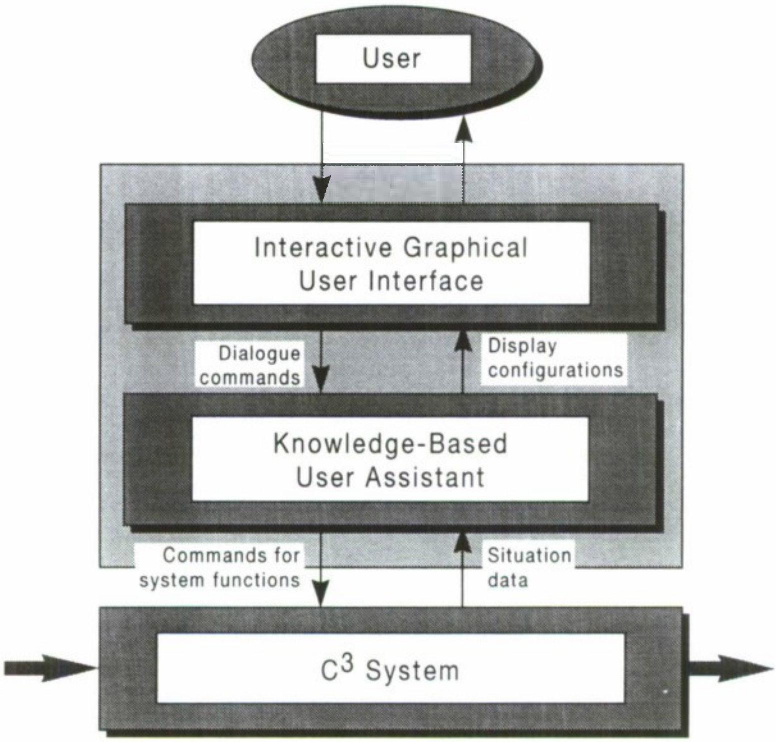

Figure 9.2. Structure of a knowledge-based user interface.

The operator should be involved in the decision-making process as long as his or her abilities are sufficient. An aid is provided only to enhance human abilities (e.g., in detecting and evaluating complex patterns or reacting to unforeseen events), to overcome human limitations, and to complement individual human preferences.

This idealistic concept is based on the philosophy of human-centered automation and envisions a computerized assistant that behaves like a human partner to the operator, that is, it can be commissioned and automatically takes over tasks. Like the operator, the assistant monitors states of the system and the environment and, in parallel, the actions of the operator (Figure 9.2). If it encounters emergency situations or inappropriate operator behavior, it automatically performs some operator functions. Faulty behavior of the operator will be identified, announced, and, if there is no reaction from the operator, possibly corrected by the assistant. This concept prefers the idea of variable rather than fixed automation. The automation is related to the classic problem of allocation of functions between humans and machines, but, in this approach, automation is adapted to different situations, missions, tasks, etc.

One of the key issues in adaptive automation concerns the method by which adaptation is accomplished. Two main approaches can be distinguished (Rouse, 1991; Parasuraman, Bahri, Deaton, Morrison, & Barnes, 1992). The operator-driven approach considers the actual state of the operator, which can be identified by measuring and/or modelling operator performance. The event-driven approach considers critical situation events that arise during a mission, for example, by state changes of the tactical situation or the system.

Most adaptive systems are based on the event-driven approach, which later can be supplemented by the operator-driven approach. Therefore, we also used the first approach in initiating development of a knowledge-based user assistant. In this method, the implementation of automation is linked to the occurrence of specific tactical events. Such an automation method is inherently flexible because it can be tied to current military doctrine during mission planning (Parasuraman et al., 1992).

THE KNOWLEDGE-BASED USER ASSISTANT (KBUA)

A concept for an aiding system to support the decision-making task of the principal warfare officer (PWO) in Navy combat information

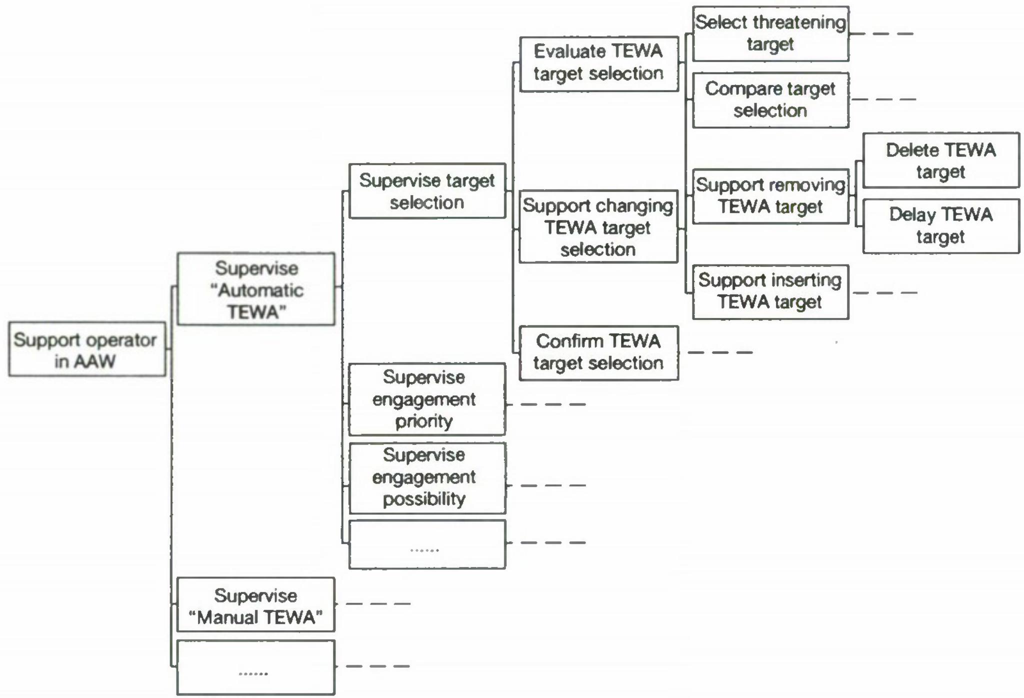

Figure 9.3. Hierarchy of operator support functions (partial) for support of the principal warfare officer in supervising automatic threat evaulation and weapon assignment (TEWA) in anti-air warfare (AAW).

centers (CICs) on board ships has been developed. In general, CIC functions to be performed by the PWO are situation assessment, action planning, action command, and checking of action accomplishment. During a mission, assessments are made about different aspects of situations, including states of the tactical and physical environment, states of personnel and the logistic supply, and states of the ship and its subsystems (e.g., sensor, effector, and propulsion subsystems, etc.).

At present, we are working on an aiding concept that supports the operator (i.e., the PWO) especially in threat evaluation and weapon assignment (TEWA) in antiair warfare situations. To identify functions for supporting the operator during these situations, a top-down function analysis (Beevis, 1992) has been performed. The resulting functional hierarchy contains different levels with functions of decreasing complexity, part of which are shown in Figure 9.3. In this figure, the decomposition proceeds from left to right. For instance, the high-level function "Supervise target selection" has been decomposed into subfunctions such as "Evaluate TEWA target selection," "Support changing TEWA target selection," and "Confirm TEWA target selection." The decomposition of the subfunction "Evaluate TEWA target selection" continues with its subfunctions "Select threatening target" and "Compare target selection."

As part of an adaptive aiding concept, each of the identified operator support functions in Figure 9.3 is conceived as consisting of four functional components: "Monitor situation," "Monitor dialogue," "Select action," and "Specify display." Figure 9.4 depicts the general structure of an operator support function with its four components and their input/output relations. The inputs and outputs of the generalized operator support function in Figure 9.4 have the same generalized categories as that of the knowledge-based user assistant (KBUA) in Figure 9.2, that is, dialogue commands and situation data inputs, and system function commands and display configuration outputs. Every function thus contributes to all aspects of the KBUA. For instance, in reaction to the detection of an environmental situation event, any function on any function level could give prompts both to the controlled TEWA process and to a corresponding display configuration on the user interface.

The functional component "Monitor situation" of an operator support function supports the first two steps of human decision making—data collection and hypotheses generation (Figure 9.1). This component

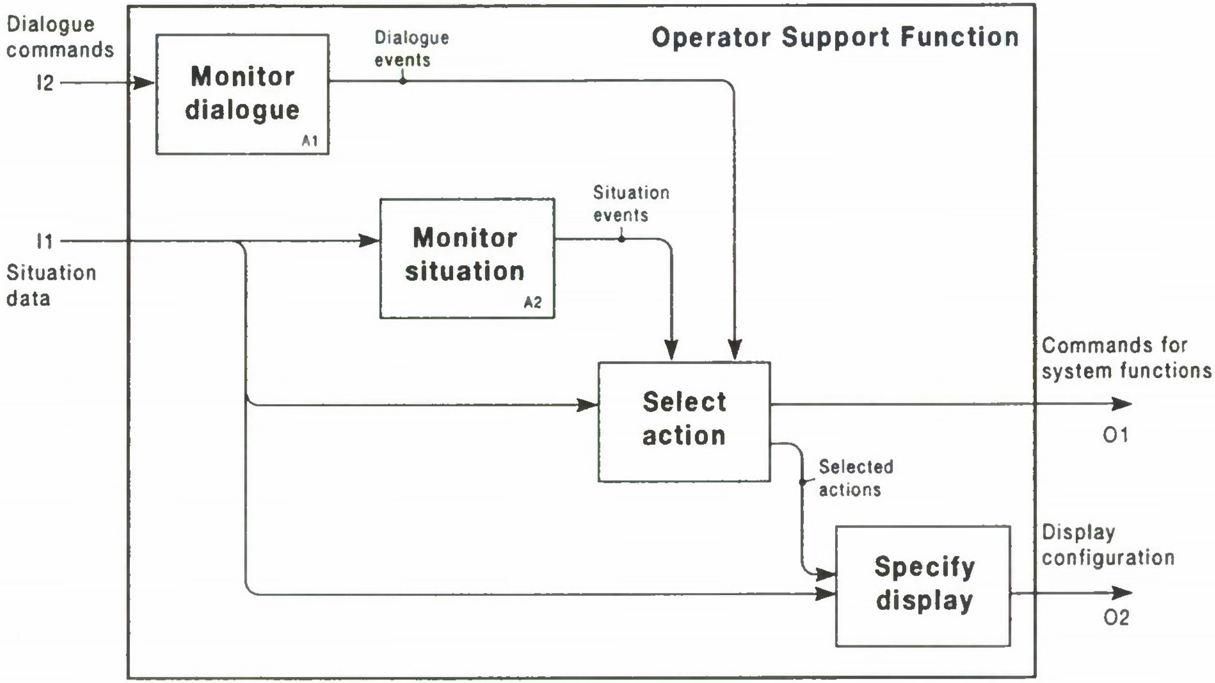

Figure 9.4. General structure of an operator support function.

reviews situation-relevant data and decides about the current state of affairs. If a situation event has been detected, it is given to the functional component "Select action" to perform appropriate actions. The component "Select action" is to support the operator in performing the third step of human decision making (Figure 9.1)—option generation, evaluation, and selection—by identifying all actions that are necessary and possible for responding to the current situation event. Normally, all actions identified and evaluated are provided by the "Specify display" component to the PWO, who decides which action should be taken. In critical threat situations, for example, incoming air-to-surface missiles detected within critical envelopes, a reaction process is executed without PWO intervention. In this case, the component "Select action" generates commands for required fast automatic system functions (Figure 9.4). The resulting decision about this automatic reaction is also presented to the PWO via the "Specify display" component. For each situation, the appropriate display and dialogue elements are stored as display resources. To assist the operator in an actual situation, the component "Specify display" activates the corresponding elements and presents them via the graphical user interface.

The operator dialogue commands are monitored by the functional component "Monitor dialogue," which helps the operator avoid negative consequences of inappropriate commands. This component compares the actual dialogue commands with those that are permitted given the present situation and sends the resulting dialogue events to the "Select action" component. If an actual dialogue command does not correspond to what is permitted, the component "Monitor dialogue" blocks its execution and provides a prompt to the PWO via the graphical user interface.

For each operator support function, three different successive states have been defined: inactive, monitoring, or active. When a function is inactive, none of its functional components is in operation. When a function is in the monitoring state, only the two functional components "Monitor situation" and "Monitor dialogue" are operating and no output is generated. In the active state, all of the four functional components shown in Figure 9.4 are in operation. An inactive function in the function hierarchy will be transferred automatically into the monitoring state if its encompassing function on the next higher level of the hierarchy is active (Figure 9.5). A function will be active if the monitoring

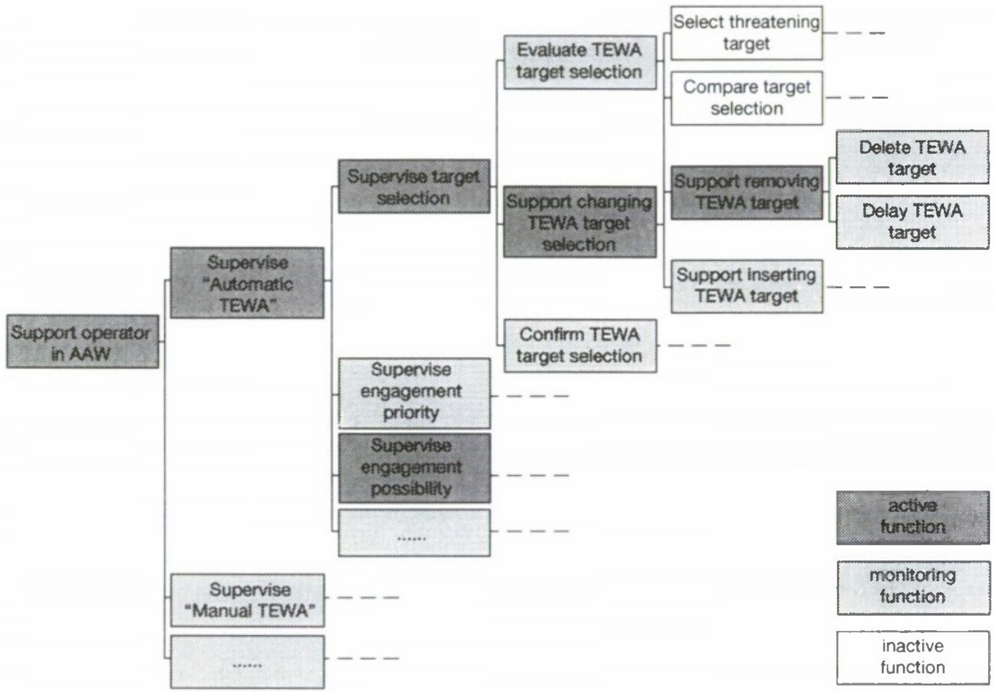

Figure 9.5. Example of operator support functions and their states during support of the principal warfare officer in supervising target selection during automatic threat evaluation and weapon assignment (TEWA) in anti-air warfare (AAW).

components detect an activation event. The function changes its state from active to monitoring if the monitoring components detect a deactivation event.

The example shown in Figure 9.5 represents a situation in which the KBUA supports the PWO in supervising target selection during an automatic TEWA. In this case, the KBUA decided that a target should be deleted from the list of engageable targets. In the activated operator support function "Support removing TEWA target," the functional component "Specify display" gives the reason for this decision via the graphical user interface to the PWO, who has to agree.

If the PWO acknowledges the KBUA decision by pressing the "Delete" button at the user interface, the function "Delete TEWA target," which is now in the monitoring state, will be activated and a deletion command for the TEWA function will be generated. The PWO can also decide to delay the engagement by pressing the "Delay" button. Then the operator support function "Delay TEWA target," which is in the monitoring state, will be activated and a delay command will be given to the TEWA system process. After sending the command, the function itself will be stopped and the encompassing function "Support removing TEWA target" eventually will be deactivated.

The hierarchically structured operator support functions (Figure 9.3), together with their four functional components "Monitor situation," "Monitor dialogue," "Select action," and "Specify display" (Figure 9.4), constitute the concrete functional model of the KBUA shown in Figure 9.2 for a specific application, in this case for supporting the operator in antiair warfare situations. The event-oriented control of each function described here enables the KBUA to react to environmental situations. Depending on an actual event, a subfunction for controlling automatic system functions or for prompting required operator actions will be activated. In this way, the support concept allows a situation-dependent activation of automatic system functions or required operator actions in an adaptive manner for every function. The great adaptability of the KBUA is seen in its ability to react to a broad variety of situations. It should be stressed that all of these situations have to be analyzed and functionally modelled for the concrete support system.

Each operator support function in the function hierarchy has to be described in a form that contains function-related specifications; for example, activation events, deactivation events, information-processing procedures, control commands for system functions accomplished auto-

matically, relevant display information and action requirements for the operator, display elements for presenting the information and possible actions on the graphical user interface, and subfunctions.

OBJECT-ORIENTED IMPLEMENTATION OF THE KBUA

For supporting the implementation of the functional KBUA model and prototyping the human-machine interface of the PWO, we applied an object-oriented approach (e.g., Coad & Yourdon, 1991; Embley, Kurtz, & Woodfield, 1992; Rumbaugh, Blaha, Premerlani, Eddy, & Lorensen, 1991) that results in an object-oriented KBUA model. An object is considered to be an encapsulated entity that accepts messages for activating its processes and changing its state, and sends messages to other objects. The central part of this object-oriented KBUA model consists of a hierarchy of objects analogous to the function hierarchy (Figure 9.3). Just as every encompassing function consists of subfunctions, every aggregate object consists of a set of subobjects. As with a function, three different states of an object can be distinguished: inactive, monitoring, and active. Figure 9.6 depicts an object with its states, state transitions, and the messages it accepts and delivers.

As in the generalized function input and output shown in Figure 9.4, an object receives messages with situation data and dialogue commands and sends messages with display configurations and commands for system functions (Figure 9.6). It also receives enabling and disabling messages from its aggregate object and sends enabling and disabling messages to its subobjects. The enabling and disabling messages received cause the corresponding events within the object. Messages in the form of situation data and dialogue commands cause activation and deactivation events within the object. As schematized in Figure 9.6, these triggering events cause state transitions with accompanying actions.

In general, a functional object has data and procedural aspects; that is, it is characterized by data (properties) and will activate procedures. Data are peculiar to each object, for example, its state. Procedures specify the functional components of an operator support function as described above, that is, "Monitor situation," "Monitor dialogue," "Select action," and "Specify display." As with an operator support function, in the monitoring state of an object, "Monitor situation" and "Monitor dialogue" procedures are in operation. In the active state of an object,

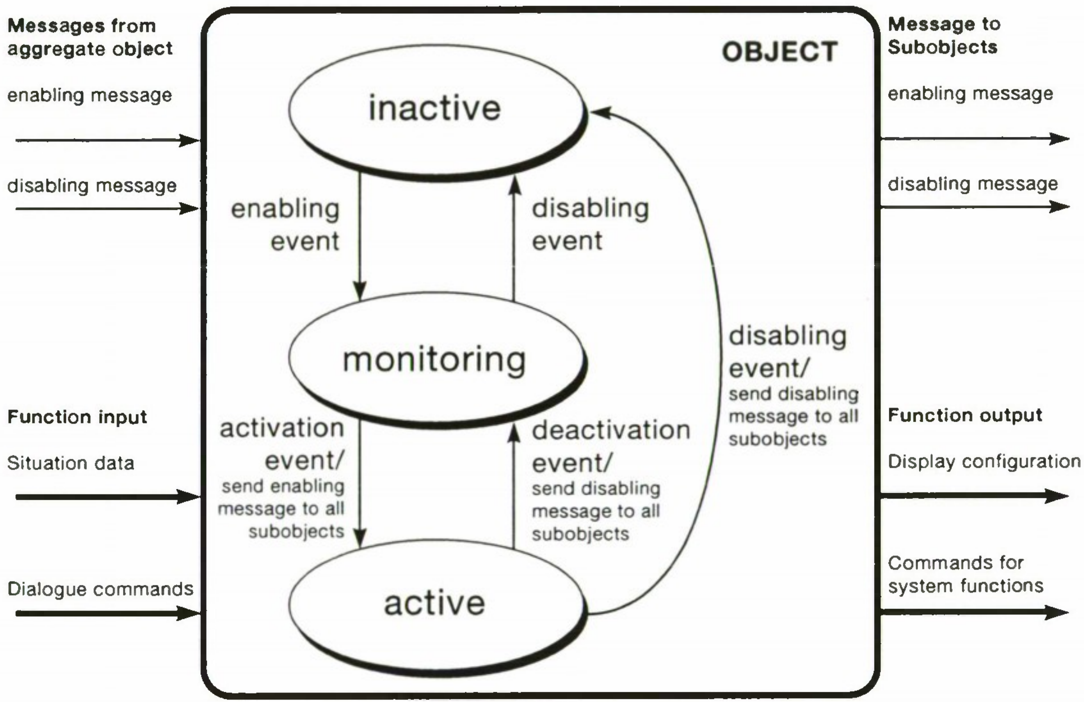

Figure 9.6. Messages and state transition structure of an object.

"Select action" and "Specify display" procedures will also be performed. "Monitor situation" and "Monitor dialogue" procedures generate activation and deactivation events by interpreting situation data and dialogue commands. They are specified as rules describing the event conditions. "Select action" procedures are represented by information-processing algorithms that generate commands for system functions and data used internally.

"Specify display" procedures are implemented as a set of control commands that describe the display configuration messages. The display system decodes these messages and activates appropriate display elements (e.g., windows, icons, menus, buttons, etc.). These display elements will be added to the interactive graphical user interface, for instance, to the display configuration already provided by activation of parallel or higher-level objects. When objects are suspended or terminated, the affiliated information and action alternatives are removed from the interface.

Figure 9.7 shows the resulting structure of the implemented object-oriented KBUA model. The object hierarchy presented is equivalent to the structure of the functional hierarchy of operator support functions shown in Figure 9.3. Each object presented in Figure 9.7 behaves as described above. In this way, every object contributes to the overall behavior of the knowledge-based user assistant depicted in Figure 9.2. An advantage of this object-oriented KBUA model is its easy adaptation to additional requirements. More objects and subobjects can be added for additional situation events and their corresponding functions and subfunctions identified during the analysis.

A prerequisite for constructing this object-oriented KBUA model is a thorough identification of the functional model, that is, all relevant events and initiated functions, and the analysis of those functions and their affiliated information/action requirements. These items can be identified by an analysis that starts with the mission of the system and its planned operations. But the analysis should be performed anyhow when human-machine interfaces are designed and prototyped (Beevis, 1992). The functional and object-oriented KBUA models described above serve as conceptual frameworks for the analysis in the problem domain. They already contain all classes of subobjects mentioned along with their necessary properties and methods. In addition, the object-oriented model resulting from the analysis represents a design description of the KBUA that serves as a basis for its implementation.

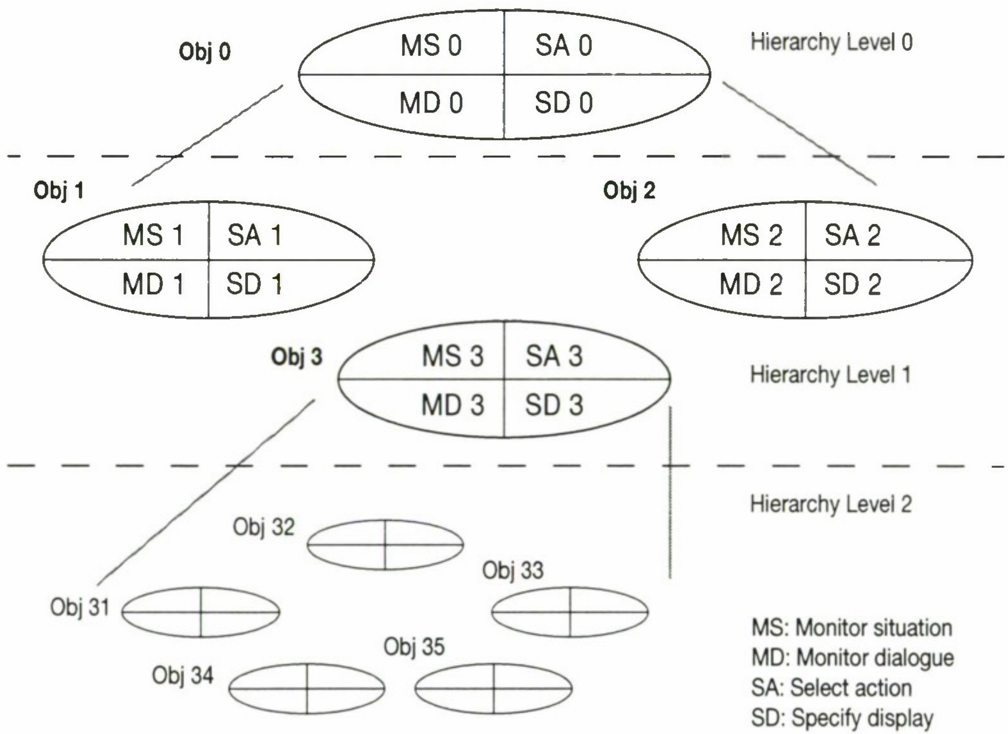

Figure 9.7. Principle of the object hierarchy.

THE PROTOTYPING APPROACH

A prototyping approach will be applied in developing the human-machine interface of the PWO and using it as a demonstrator. This approach supports the trend in the development of computer applications of shifting power from specially trained programmers to domain experts and users. This trend will also force development organizations to bring users into system design as early as possible and finally accept prototyping as a legitimate technique.

Prototyping is the construction of a (software) product by iterative design, in which a user interface is included from the beginning and, in most cases, a simulator of a controlled or monitored system is incorporated. The prototyping approach does not mean building and testing a prototype and then creating a new system with another language and another hardware system corresponding to this prototype. Here, the prototype itself becomes the system. Prototyping is an iterative and incremental approach to the construction of systems.

The requirements for many military systems are not clear at the beginning. This is especially true for the design of user interfaces. In the prototyping approach, one can start with a very simple design (e.g., an existing design), let it be evaluated by military users, and augment it from time to time in an iterative manner with a better version adapted to new requirements. In this way, the user can be involved in very early design stages, and the role of the user is implicit. Therefore, the system will be better accepted by users, and most requirements will be better understood by them. The prototyping approach that we apply starts with a relatively simple mission and a very simple function model reacting to only a few events.

We began by describing a multithreat situation in an antiair warfare mission of a ship and identifying relevant mission events and functions of the PWO. The identified mission functions are basic data for designing the function hierarchy. The conditions of relevant mission events specify the rules of the "Monitor situation" procedures of each function. Further, information/action requirements have been identified for each function as a basis for the "Specify display" component. These data are used to develop display layouts using the illustration and designing tool MacroMind. The layouts have been and will be discussed with experienced users for acceptance and improvements. By decomposing these

layouts into their elementary units, it was possible to identify required display and dialogue elements of the display manager.

The object-oriented KBUA model is independent of a specific computer language or implementation system. To implement the interface demonstrator, we installed the model on a DEC-VAX station with the expert system shell Smart Elements. Other components of the demonstrator are two pixel-oriented screens with pointing devices and a keyboard. The model is implemented with those object-oriented features and rules that Smart Elements offers. The graphical output and dialogue features of Smart Elements are used as an interactive graphical interface.

REFERENCES

Amalberti, R., & Deblon, F. (1992). Cognitive modelling of fighter aircraft process control: A step towards an intelligent on-board assistance system. *International Journal of Man-Machine Studies, 36,* 639-671.

Anderson, J. R. (1988). *Kognitive Psychologie.* Heidelberg: Verlag Spektrum.

Banks, S. B., & Lizza, C. S. (1991, June). Pilot's associate: A cooperative, knowledge-based system application. *IEEE Expert, 1,* 18-29.

Beevis, D. (Ed.). (1992). *Analysis techniques for man-machine systems design* (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

Coad, P., & Yourdon, E. (1991). *Object-oriented analysis* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Cohen, M. S., Thompson, B. B., & Chinnis, J. O. (1985). *Design principles for personalized decision aiding: An application to tactical air force route planning.* Griffiss Air Force Base, NY: Air Force System Command, Rome Air Development Center.

Dudek, H. L. (1990). *Wissensbasierte Pilotenunterstützung im Ein-Mann-Cockpit bei Instrumentenflug.* Doctoral dissertation, Universität der Bundeswehr München.

Edwards, D. C. (1990). *Pilot: Mental and physical performance.* Ames, IA: Iowa State University Press.

Embley, D. W., Kurtz, B. D., & Woodfield, S. N. (1992). *Object-oriented analysis, a model driven approach.* Englewood Cliffs, NJ: Prentice-Hall.

Parasuraman, R., Bahri, T., Deaton, J. E., Morrison, J. G., & Barnes, M. (1992). *Theory and design of adaptive automation in aviation systems* (Progress Report No. NAVCADWAR-92033-60). Warminster, PA: Air Vehicle and Crew Systems Technology Department, Naval Air Warfare Center, Aircraft Division.

Rouse, W. B. (1991). *Design for success —A human centered approach to designing successful products and systems.* New York: Wiley.

Rouse, W. B., Geddes, N. D., & Curry, R. E. (1988). An architecture for intelligent interfaces: Outline of an approach to supporting operators of complex systems. In W. B. Rouse (Ed.), *Human-computer interactions, 1987-1988* (Vol. 3, pp. 87-122). Hillsdale, NJ: Lawrence Erlbaum.

Rouse, W. B., Geddes, N. D., & Hammer, J. M. (1990, March). Computer-aided fighter pilots. *IEEE Spectrum,* 38-41.

Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F., & Lorensen, W. (1991). *Object-oriented modelling and design.* Englewood Cliffs, NJ: Prentice-Hall.

Sage, A. P. (1991). *Decision support systems engineering.* New York: Wiley.

Wickens, C. D. (1984). *Engineering psychology and human performance.* Columbus, OH: Merrill.

Wittig, T., & Onken, R. (1992, 11 June). Knowledge-based cockpit assistant for controlled airspace flight-operation. *Preprint 5th IFAC Symposium on Analysis, Design, and Evaluation of Man-Machine Systems.* The Hague, The Netherlands.

Wohl, J. G. (1981). Force management decision requirements for air force tactical command and control. *IEEE Transactions on Systems, Man, and Cybernetics, 11*(9), 618-639.

10

HUMAN-CENTERED COCKPIT DESIGN THROUGH THE KNOWLEDGE-BASED COCKPIT ASSISTANT SYSTEM (CASSY)[1]

R. Onken

This paper presents basic requirements for cockpit systems that promote improved human-machine interaction. Such an approach is often called "human-centered automation" or "human/machine function allocation." Human-centered automation in its true sense means enhancing flight safety and mission effectiveness. The time has come when future cockpit systems no longer will be designed on the basis of vague specifications to achieve human-centered automation. Advances in technology make it possible systematically to translate requirements for human-centered automation into clear-cut specifications for cockpit systems. Machine functions should be incorporated that provide more than just support for planning and plan execution, as emphasized in the past. Instead, the main emphasis should be on autonomous machine situation assessment in parallel with the crew's situation assessment activity, which leads to better machine understanding of the crew's real needs. The Cockpit Assistant System (CASSY) was developed to meet these requirements.

INTRODUCTION

Regardless of whether the application is civil or military, the objective of a flight mission is to accomplish that mission without loss of human life or equipment. Thus, flight safety obviously is of paramount

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concern. Every accident that has occurred, for whatever deplorable reason, is one accident too many.

Investigations into accidents in civil aviation and their causes provide ample evidence of the fact that erratic human behavior is the main contributing factor in about 75 percent of all such accidents. It can be claimed that these human failures are caused by some kind of overtaxing,[1] sometimes clearly realized and sometimes not even noticed until it is too late. In this context, overtaxing is considered to describe the situation that arises when human failure threatens because of inherent human deficiencies in sensory, cognitive, and motor capabilities and performance. As automation in the aircraft cockpit has increased, new types of situations have arisen that are prone to latent overtaxing, especially those involving failures in situation awareness due to human cognitive limitations. Recent accidents involving highly automated civil transport aircraft, which have gained great public attention, provide evidence of this trend.

The potential hazard of overtaxing the cockpit crew in certain flight situations calls for even more automation, which I explicitly want to support as the reasonable way to proceed. Automation itself should not be blamed for potentially overtaxing the crew. The question of *how to automate* does have to be raised, however. The way automation has been pushed forward in the past must be scrutinized.

Automation has been advancing by respecting certain principles regarding the role of the human—which should by no means be changed—and by following a certain scheme of *function allocation* to the crew, on the one side, and to technical components, the machine, on the other. Figure 10.1 illustrates the functions allocated currently to the aircraft systems and those the crew is trained to perform. There are some functions (usually not considered allocated) that are permanently turned on, such as the basic cockpit instrumentation and actuator machinery for power amplification, and other functions that are activated by the crew and thus allocated to carry out certain tasks in place of the crew.

Function allocation is not as easy a task as it might appear at first glance. Major driving factors for allocating functions or parts of functions to the machine in one way or another are the potential for reduc-

[1] The term *overtax* is used here instead of the more common term *overload* to separate the concept from associations with workload and to include situations where humans cannot cope because of lack of abilities.

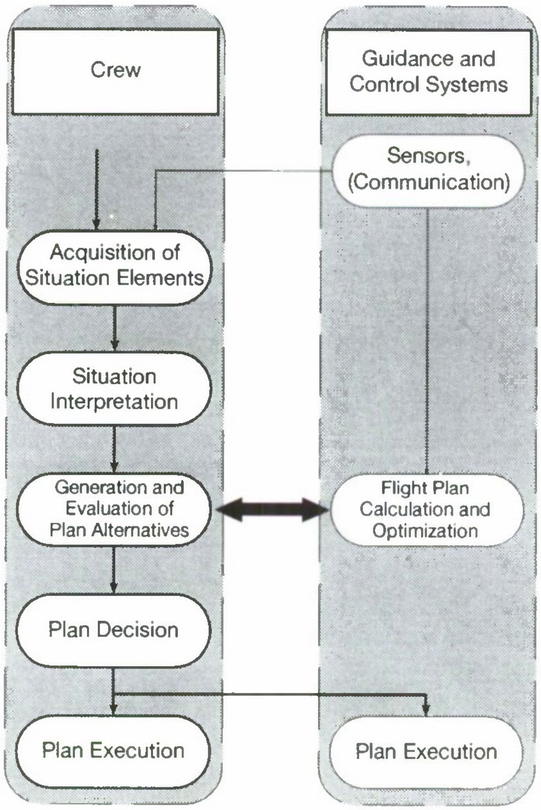

Figure 10.1. Flight guidance and control today.

ing crew workload—letting the machine do what it can do better—and demonstration of technical feasibility. Technical feasibility has often seemed to be considered sufficient reason for automating certain functions, whatever the type of allocation, in the hope that some kind of overall system improvement and crew workload reduction will result. To let the machine do what it seems to do better, however, might lead accidentally to allocating certain functions to the machine when parts of these functions actually could be carried out much better by the crew. As Billings (1991) has noted: "While it clearly makes sense to apportion to the man and the system respectively those aspects of the task that each does best, there are no infallible rules to define these proficiencies."

Obviously, the principle of function allocation as it has been deployed so far can lead to problems. This is especially true for automated functions that are not thoroughly scrutinized in terms of their impact on overall mission performance. There is a steadily increasing number of permanently activated machine functions of which the pilot must keep track. At the same time, there are more and more deployable machine functions that can be activated at the option of the crew. The situation can become very complex to keep under control, since the crew must also be ready at any time to take over all parts of functions that are not covered by any machine. This raises two obvious concerns with regard to allocating functions to the machine in current operational systems:

- Permanently allocated functions are often event driven and operate in the background. Resulting changes in constraints for maneuverability and pertinent consequences might not be apparent to the crew and might lead to overtaxing of the crew in situation assessment.
- Functions intentionally activated by the crew might unexpectedly demand far too much attention from the crew because of complex handling.

Consequently, it is not surprising that increasing automation with no well-established way of allocating functions to avoid the pitfalls mentioned above implies an increased potential for new types of crew overtaxing and the resulting human failures, that is, mission hazards. Dealing in the most efficient way with the limited resources of human attention is paramount. Therefore, new ways of automation must be

established through top-down structuring of fundamental requirements. On the basis of these requirements, machine functions can be specified that truly serve mission accomplishment. To describe this approach in more detail is the main purpose of this paper.

THE FLIGHT MANAGEMENT SYSTEM

In a US investigation into aspects of the interaction between human and machine in the cockpit (Wise et al., 1993), some of the problems with the flight management system were highlighted. Other investigations came to similar conclusions.

The flight management system receives information about the actual flight, including data about the destination, the flight plan to the destination with way points and altitudes, weather information, and load weight. When all this information is keyed into the system by the crew (which can become a significant interactive effort), the flight management program can be initialized. From then on, the aircraft can fly autonomously unless changes of inputs have to be keyed in because of unexpected occurrences in the overall flight situation. The investigation concluded that pilots run into difficulties in time-critical situations with unforeseen impacts, such as receiving new air traffic control instructions. In such situations, there is not enough time to enter the necessary inputs and interpret the computational results delivered by the flight management system. These are the situations in which the pilots might be left on their own (Wiener, 1989; Amalberti & Deblon, 1992; Sarter & Woods, 1993) with questions like:

- What is it doing?
- Why did it do that?
- What will it do next? or
- How did it ever get into that mode?

Thus, the flight management system is usually turned off in just the situations where pilots are looking hungrily for assistance (Heldt, 1993). These obvious deficiencies clearly indicate that the goal of automating the cockpit to increase flight safety has fallen somewhat out of sight. Therefore, it is time now to reconsider the basic requirements for machine support in the cockpit, especially with regard to situation assessment tasks of the crew, including sensory and information-processing functions.

BASIC REQUIREMENTS FOR COCKPIT AUTOMATION

There are a great number of well-formulated requirements at hand for human-machine interaction in the cockpit, including those for "human-centered automation" (Billings, 1991). To guide future automation so it meets the aims of human-centered automation, however, one must be able to assess how much certain individual requirements from the long list of existing ones contribute to the design goals, particularly when trade-offs become necessary. Therefore, a top-down structure comprising the minimum set of basic requirements is needed to ease the engineering task of converting these requirements into a technical product. Such a structure will be described in what follows.

To resolve this problem, we ask, first, what is to be achieved by automation? What is the objective of automating pilot functions? This can be answered very quickly by the following general statement: Overtaxing of the cockpit crew, as defined earlier, is to be avoided. This means that the demands on the cockpit crew must be kept at a normal level for all situations and situation-dependent tasks, subject to certain task categories in the domains of flight control, navigation, communication, and system handling, such as:

- situation assessment;
- planning and decision making;
- plan execution.

For these task categories, the following priority list of basic requirements, organized as a two-level hierarchy, can be established (Onken, 1993). These requirements are essentially equivalent to the requirements for human-centered automation as stated in Billings (1991), except that they are structured from an engineering perspective. They can be formulated as follows:

- To avoid overtaxing the crew in situation assessment, the top requirement, *Basic Requirement 1,* should be met, that is:

  In the presentation of the full picture of the flight situation, it must be ensured that the attention of the cockpit crew is guided toward the objectively most urgent task or subtask of that situation.

- To avoid or decrease overtaxing of the crew in planning and decision making as well as plan execution, as a *subordinate* requirement, *Basic Requirement 2* can be formulated:

  If basic requirement 1 is met, and if overtaxing of the cockpit crew (in planning or plan execution) still occurs, then this situation must be transformed, by the use of technical aids, into a situation that can be handled by the crew in a normal manner.

This particular top-down formulation of requirements for human-centered automation distinctly makes clear that, whatever the technical specifications for a cockpit crew support system, they are questionable if the specification for the situation assessment capability of the support system (basic requirement 1), including the assessment of the crew's situation, is too neglectful and sloppy. How can the support system work to direct the crew's attention if it cannot assess the global situation on its own? If the system is unable to understand the underlying situation, it might work from the wrong assumptions! Thus, if the specification fails to fulfil basic requirement 1, this failure cannot be compensated by any automated support designed to comply only with requirement 2.

Unfortunately, inadequacy caused by disregarding basic requirement 1 was commonly the case in the past, because technical means were not available for comprehensive situation assessment by the machine. Prevention of crew overtaxing in situation assessment was not worked into the specification in the systematic manner suggested by basic requirement 1.

Basic requirement 1, in fact, necessarily leads to the full set of specifications, which in turn can be used to verify human-centered automation design.

APPLICATION OF THE BASIC REQUIREMENTS IN SYSTEM DEVELOPMENT

Obviously, according to basic requirement 1, the main issue is to carefully specify the situation assessment portion of the machine functions. The picture of the flight situation generated by the machine should cover all aspects of the situation that also need to be considered by the cockpit crew. Moreover, it would be most desirable if the machine picture were to be even more comprehensive and more accurate.

This is already feasible today for certain aspects. In principle, therefore, compliance with basic requirement 1 can be accomplished with the technology at hand.

In essence, the capability of situation assessment is to be incorporated into the machine part of the human-machine system by assigning the corresponding functions in parallel to the machine as well as to the cockpit crew (Figure 10.2). In addition, the machine part is monitoring the cockpit crew, and thus has the full picture, including the crew situation. This is the basis for cooperative automation so that the attention of the cockpit crew can be guided toward the objectively most urgent task or subtask of the actual situation.

It becomes evident at this point that, instead of allocating functions either to the machine or to the crew once and for all, all functions necessary to fly the aircraft are not only inherent crew functions but also functions the machine should be able to perform. All of them are operative in parallel unless effector actions are to be executed. Thus, there is no conflict with the principle that it is generally up to the crew to make the final decision about whether to accept an action recommended by the machine or to follow their own ideas. We call this *situation-dependent function sharing of human and machine as partners.*

Partnership means that the capabilities of the partners are similar, but not necessarily identical. Partnership demands effective dialogue. According to basic requirement 1, the presentation of the full picture of the situation must be shaped in such a way that the crew's attention is guided by the presentation only if necessary. In addition, the crew should be able to talk to the machine partner just as the crew members communicate with each other. Therefore, in summary, the key specifications for the development of new generations of cockpit automation concern both:

- comprehensive machine knowledge of the actual flight situation; and
- efficient communication between crew and machine, based on situation knowledge and new dialogue technology.

How can the machine's knowledge about the actual flight situation be established in order to meet these specifications? Both advanced techniques for structured knowledge representation and information processing based on advanced sensor technology (e.g., voice recognition and computer vision) make it possible to generate a knowledge base that

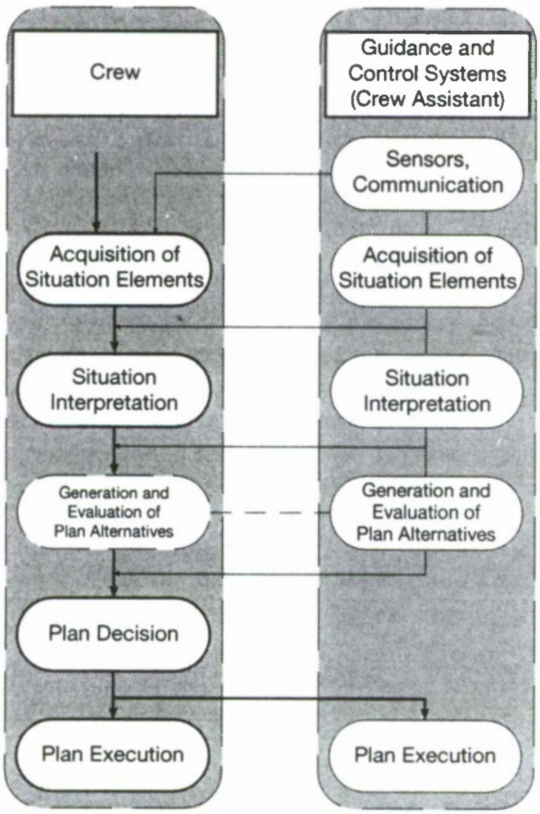

Figure 10.2. Flight guidance and control in the future.

includes nearly all static and dynamic situation elements the cockpit crew may be aware of and possibly even more than that. Of concern here are the task-related situation elements as well as the elements pertinent to the main players, such as the world surrounding the aircraft, the aircraft itself, and, probably most important, the cockpit crew.

Knowledge about the cockpit crew is crucial. Objective knowledge about the crew can be of paramount value. On the one hand, the machine might have a better picture of the pilot's status than the pilot does, especially in situations of imminent overtaxing. On the other hand, machine knowledge about the crew is the basis for crew-adapted assistance. The machine cannot assist in an efficient way if it does not sufficiently understand the activities and corresponding needs of the cockpit crew. In its most advanced elaboration, knowledge about the cockpit crew comprises models of physical and mental resources as well as behavioral models (see Figure 10.3). Therefore, crew behavior for situation assessment, planning, and plan execution is to be modelled for normative behavior as well as individual behavior. Knowledge about the crew member's individual behavior has to be learned on line by the

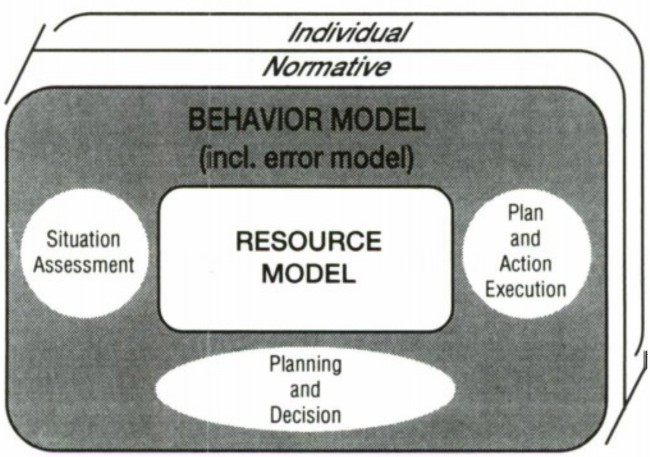

Figure 10.3. Model of the cockpit crew.

machine. The modelling of error behavior is another important behavioral aspect to be covered. Crew action modelling should not be confined to activities with hands and feet; eye and head motion, as well as voiee aetivity, also eontain important information and have implications for efficient communication management between machine and crew.

In summary, the previous two sections have outlined in very general terms the main guidelines that should be followed as closely as possible to achieve truly human-centered automation. These guidelines ean easily be formulated as system design specifications. There are already examples of sueeessful development programs, such as those described in Strohal and Onken (1994), which have proven that translating the basic requirements into system concepts and implementation can be accomplished successfully in the way described here.

THE COCKPIT ASSISTANT SYSTEM (CASSY)

The following description of the Cockpit Assistant System, CASSY (Gerlach & Onken, 1994), is presented as an example of how to design a system to comply with the ideas discussed above. CASSY was developed at the University of the German Armed Forees in Munich (Universität der Bundeswehr München) in cooperation with DASA-Dornier.

The previous sections pointed out the importance of electronic situation understanding for successful machine support. A system can understand a situation only if it has the appropriate knowledge of the problem spaee in which it works. Since CASSY is limited to civil aviation, its knowledge base comprises the elements of Figure 10.4.

This knowledge base is characterized by static knowledge, for example, a normative model of cockpit crew behavior or knowledge of the aireraft used, and dynamie knowledge, such as changing circumstances during flight caused by instructions from air traffic control (ATC) or environmental influences. Stored in a central situation representation, this knowledge serves as a global picture of the current situation.

In order to gather dynamie knowledge and to transmit its conclusions, the cockpit assistant system is placed in the flight deck. CASSY has interfaees to the flight crew, to the aircraft, and to ATC. The interfaces ensure that all knowledge sources are available for the task-specific

modules of the system. A diagram of CASSY is shown in Figure 10.5.

The *Automatic Flight Planning* module generates a complete global flight plan (Prevot & Onken, 1993). On the basis of its knowledge of mission goal, ATC instructions, aircraft systems status, and environmental data, an optimized 3D/4D trajectory flight plan is calculated. The flight plan (or several plans) is presented as a recommendation that the crew accepts or modifies. Once a flight plan is chosen, it serves as a knowledge source for other CASSY modules. The Automatic Flight Planning module recognizes conflicts that may occur during the flight, for example, due to changing environmental conditions or system failure, and appropriate replanning is initiated. If necessary, this replanning process includes the evaluation and selection of alternate airports. Since the module has access to ATC instructions, radar vectors are incorporated into the flight plan autonomously and the system estimates the probable flight path ahead.

The presentation of the resulting situation-dependent flight plan to the crew directly serves basic requirement 1 discussed above and provides

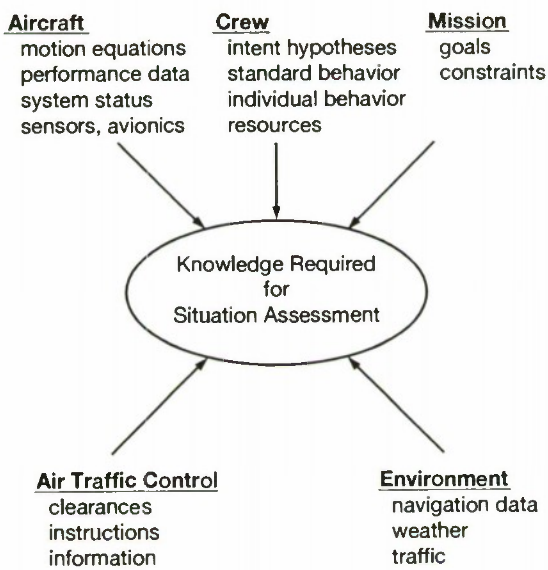

Figure 10.4. Knowledge base of the Cockpit Assistant System (CASSY).

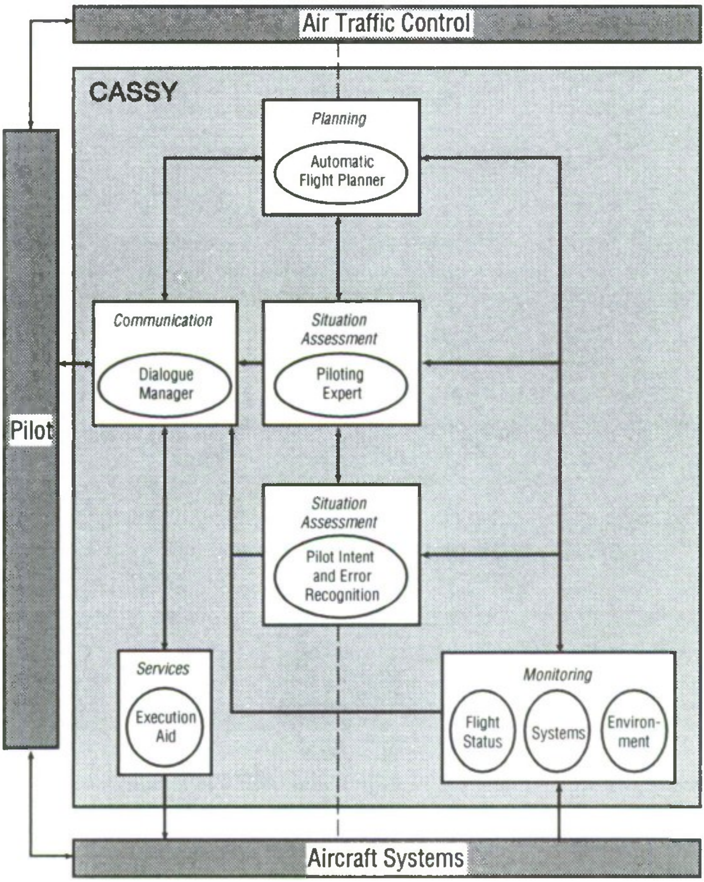

Figure 10.5. The Cockpit Assistant System (CASSY).

evidence for necessary flight plan changes. The extensive aid in decision making and time-consuming flight plan calculations supports basic requirement 2.

The *Piloting Expert* module uses the valid flight plan to generate necessary crew actions. It is responsible for processing crew models of normative and individual crew behavior (Ruckdeschel & Onken, 1994). The normative model describes prescribed pilot behavior as published in pilot handbooks and air traffic regulations. The model refers to flight guidance procedures concerning altitude, speed, course and heading, as well as to aircraft systems management. Given the flight plan and a pointer on the current leg, provided by the Flight Status Monitor, the system determines the appropriate normative values and tolerances on aircraft systems and flight status data. These data are adjusted by the system to individual preferences using the individual crew behavior model, determined from an adaptive component.

The crew model used to generate necessary and expected crew actions is absolutely vital to meeting requirement 1. It enables the system to identify the most important actions on the basis of the underlying situation and to interpret the observed crew behavior.

Expected crew actions are compared with the actual behavior of the crew in the *Pilot Intent and Error Recognition* module (Wittig & Onken, 1992). Crew actions are derived indirectly by interpreting the aircraft data. If given tolerances are violated, the crew will be informed by hints and warnings, and the detected mistake is pointed out to the pilots. When the crew deviates intentionally from the flight plan, the module checks to see if this fits one of a given set of hypotheses for allowable intents that are also part of the crew model. These hypotheses represent behavior patterns of pilots in specific cases; for example, tasks to be done when commencing a missed approach procedure or when deviating from the flight plan to avoid a thunderstorm ahead. When an intentional flight plan deviation and the respective hypothesis is recognized, appropriate support (e.g., replanning) is initiated.

The monitoring of the pilots' actions and the distinction between error and intentional behavior in extraordinary situations serves both basic requirements 1 and 2. Additional monitoring modules are needed to enable the system to recognize and interpret current situations. The *Flight Status Monitor* provides the present flight state and progress. It is also able to report the achievement of subgoals of the flight.

The *Environment Monitor* gathers information on the surrounding traffic (e.g., from the traffic collision avoidance system) and weather conditions, and incorporates a detailed navigational database of the surrounding area. The operational status of aircraft systems is monitored by the *Systems Monitor* like a diagnosis system.

Obviously, the monitoring systems are essential to meet the first requirement, since their outputs are an important part of the full picture of the present situation. Because their output is also used to adjust the flight plan to the situation, they contribute to meeting the second requirement as well. In addition, the continuous observation of flight progress, environment, and aircraft systems supports the crew in tedious or horing but necessary tasks.

Communication plays an important role in CASSY. The kind of information to he transmitted in either direction varies for the different modules (Figure 10.6). The information flow from CASSY to the crew and vice versa is controlled by the *Dialogue Manager* module (Gerlach & Onken, 1993). The many different kinds of messages require processing so that the appropriate display device is used and the message is presented at the right time. Both a graphic/alphanumeric color display and a speech synthesizer are used as output devices. Short warnings and hints are used to make the crew aware of a necessary and expected action and are transmitted verbally using the speech synthesizer. A static alphanumeric line is also added to the graphic display to facilitate perception of difficult verbal messages. More complex information, for example, the valid flight plan, is depicted on a moving map on the graphic display.

Another important feature of the Dialogue Manager is that, since the tolerances and danger boundaries are given in the crew model and the necessary actions are inferred, a priority ranking of the output message is evaluated and the most important message is issued with priority.

The input information flow is established using speech recognition in addition to conventional input mechanisms. In order to improve speech recognition performance, almost the complete knowledge base of CASSY is used to provide situation-dependent syntaxes. Thus, the complexity of the overall language model is reduced significantly. Not only the pilot's inputs but also the inputs from ATC must he considered. The ATC datalink, indicated in Figure 10.6, is not yet available. Discrimination of ATC instructions from pilot input is achieved hy picking up the pilot's verbal acknowledgment of the ATC controller's

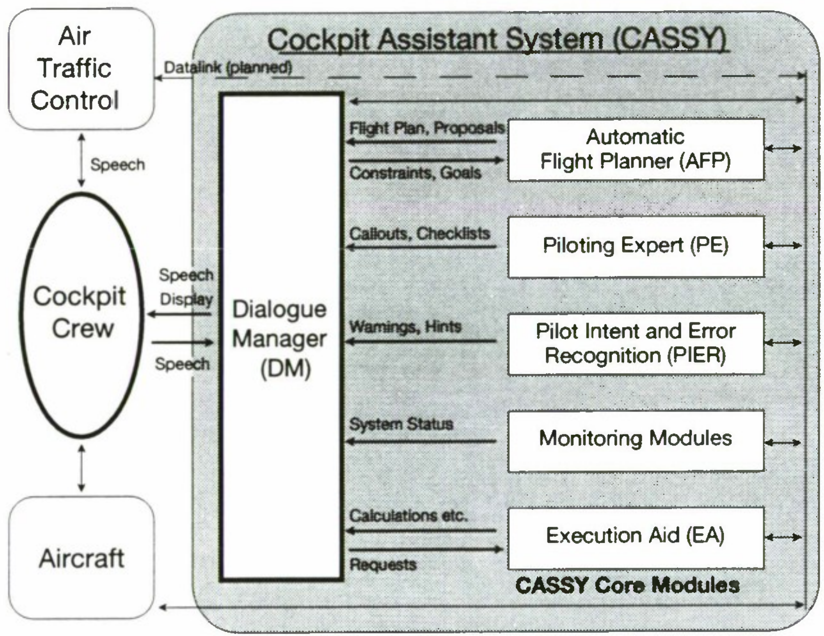

Figure 10.6. Information flow in CASSY.

instructions. The use of speech input and output devices also reflects the idea of a cooperative human-electronic crew and cooperation between partners.

In Figures 10.5 and 10.6, an additional module is shown called *Execution Aid*. This module implements several functions that can be called up by the crew. Aircraft settings, navigational calculations, and database inquiries are carried out. These functions are similar to automated functions available in today's aircraft and are designed mainly to meet requirement 2. For the pilots, the main difference is the support of speech input, which facilitates the use of these services.

RESULTS OF THE FLIGHT TESTS

In June 1994, CASSY was given 11 hours of flight test trials in Braunschweig, Germany.

The modules of CASSY have been implemented on an off-the-shelf Silicon Graphics Indigo workstation using the C programming language. A Marconi MR8 PC card was used as a speaker-dependent, continuous speech recognition system. A DECTalk speech synthesizer served as speech output device. Three different voices were used to enable the pilot to discriminate among the various messages. The components were connected using serial lines and Ethernet.

The system was integrated into the test aircraft ATTAS (Advanced Technologies and Testing Aircraft) of the German Research Institute for Aeronautics and Astronautics (Deutsche Forschungsanstalt für Luft- und Raumfahrt) in Braunschweig. The aircraft is well equipped for flight guidance experiments, since it can be operated via a single-seat, experimental cockpit located in the cabin. An Ethernet connection to the CASSY workstation was used to simulate an avionic bus system for the aircraft interface in either direction. For the ATC interface, two approaches were tested: a simulated ATC datalink and the pilot's acknowledgment of ATC instructions.

The test flights comprised instrument flights from the regional airport of Braunschweig to the international airports of Frankfurt, Hamburg, and Hannover, at which a missed approach procedure was conducted before returning to Braunschweig.

The experiments proved CASSY's functions throughout the complete flight from takeoff to landing. Speech recognition performed well in the aircraft, since the surrounding noise was primarily engine noise, which

did not change much during flight. The recognition rates were similar to those achieved in the quieter simulator environment at the university in Munich where CASSY was developed and tested earlier.

One important aspect of the tests was to prove the system in the high-density ATC of German airports, which could not be tested in simulator test runs. During the trials, any given ATC instruction could be processed and integrated into the flight plan by CASSY. Compared to available flight management systems, the autonomous integration of ATC radar vectors proved to be faster and did not lead to distracting information input.

On the basis of the flight plan, the correct expected pilot actions were generated and pilot errors, provoked or nonprovoked, were detected and the appropriate warnings issued. Wrong warnings occurred infrequently and were noncritical in any case.

Two pilots flew with CASSY in the test aircraft. Additional pilots from Lufthansa German Airlines participated to observe the tests and to serve as a second pilot beside the test pilot.

CASSY was well accepted by the pilots throughout the trials. In particular, the pilots appreciated the autonomous flight plan functions of CASSY. Warnings and hints were considered justified, and corrective system inputs were made. Speech input was generally used when complex inputs were required, for example, to enter frequency settings using the simple name of the station instead of its more difficult frequency.

CONCLUSIONS

The time has come when future cockpit systems no longer will be designed on the basis of vague specifications. Advances in technology make it possible systematically to translate the requirements for human-centered automation into clear-cut specifications for cockpit systems.

Machine functions will be incorporated that provide more than just support for planning and plan execution, as emphasized in the past. Instead, the main emphasis will be on autonomous machine situation assessment in parallel with the crew's situation assessment activity. This will lead to better machine understanding of the crew's real needs and, consequently, to more efficient support to ensure flight safety and mission effectiveness.

The Cockpit Assistant System (CASSY) is an example of how a pilot support system might look to achieve human-centered automa-

tion. It is designed to meet the basic requirements for cockpit systems as stated in this paper. The successful flight test trials with this system show that a new generation of cockpit automation systems can be introduced for higher standards in flight safety and mission effectiveness. There are already examples of successful development programs, which have proven that the method of implementing design guidelines described in this paper leads systematically to the desired system performance.

REFERENCES

Amalberti, R., & Deblon, F. (1992). Cognitive modelling of fighter aircraft process control: A step towards an intelligent on-board assistance system. *International Journal of Man-Machine Studies, 36,* 639-671.

Billings, C. (1991). *Human-centered aircraft automation: A concept and guidelines* (NASA Technical Memorandum 103885). Moffett Field, CA: NASA Ames Research Center.

Gerlach, M., & Onken, R. (1993). A dialogue manager as interface between aircraft pilots and pilot assistant system. In *Proceedings of HCI International '93*, 5th International Conference on Human-Computer Interaction, jointly with 9th Symposium on Human Interface, Japan. Orlando, FL: Elsevier.

Gerlach, M., & Onken, R. (1994). CASSY—The electronic part of a human-electronic crew. In *Proceedings of International Workshop on Human-Computer Teamwork* (pp. 159-164), Cambridge, sponsored by the US Air Force. London: Air Force Office of Scientific Research (AFMC), European Office of Aerospace Research and Development.

Heldt, P. H. (1993). *Flying the glass-cockpit.* Berlin: DGLR-Fachausschuß Anthropotechnik.

Onken, R. (1993). *Funktionsverteilung Pilot-Maschine: Umsetzung von Grundforderungen im Cockpitassistenzsystem CASSY.* Berlin: DGLR- Fachausschuß Anthropotechnik.

Prevot, T., & Onken, R. (1993). On-board interactive flight planning and decision making with the cockpit assistant system CASSY. In *Proceedings of 4th International Conference on Human-Machine Intelligence in Aerospace (HMI-AI-AS),* Toulouse, France.

Ruckdeschel, W., & Onken, R. (1994). *Modelling of pilot behaviour using petri nets.* Paper presented at the 15th International Conference on Application and Theory of Petri Nets, Zaragoza, Spain.

Sarter, N. R., & Woods, D. D. (1993). *Cognitive engineering in aerospace application: Pilot interaction with cockpit automation* (NASA contract NCC2-592). Moffett Field, CA: NASA Ames Research Center.

Strohal, M., & Onken, R. (1994). Cockpit assistance. In *Proceedings of Workshop on Human Factors/Future Combat Aircraft*, sponsored by the Four Power Air Senior National Representatives Technical Group on the Supermaneuverability of Combat Aircraft (4PWRSMTG). Ottobrunn, Germany: IABG.

Wiener, E. L. (1989). Reflections on human error: Matters of life and death. In *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 1-7). Santa Monica, CA: Human Factors Society.

Wise, J. A., Abbott, D. W., Tilden, D., Dyck, J. L., Guide, P. C., & Ryan, L. (1993). *Automation in corporate aviation: Human factors issues* (Interim Technical Report CAAR-15405-93-1, FAA). Washington, DC: Federal Aviation Agency.

Wittig, T., & Onken, R. (1992). *Pilot intent and error recognition as part of a knowledge-based cockpit assistant.* Paper presented at the AGARD Joint Flight Mechanics Panel/Guidance and Control Panel Symposium, Edinburgh, Scotland.

11

REVERSE ENGINEERING ALLOCATION OF FUNCTION METHODOLOGY FOR REDUCED MANNING (REARM)

T. B. Malone

As the availability of manpower for military systems, as well as budgets to support fielded systems, are reduced, more attention is being given to the need to reduce personnel levels in future systems compared with the level in existing systems. The major approach to reducing manning is to reallocate functions to automated performance that were previously conducted manually, thereby decreasing the workload on human operators and reducing the number of personnel required. In this strategy, the emphasis is on a redetermination of the role of the human in the system. An approach for determining the role of the human conducted for the purpose of reducing system manning below that required in the existing system is designated "REARM" (for Reverse Engineering Allocation of function methodology for Reduced Manning). REARM incorporates several of the tools available in the Carlow International HSI IDEA (human-system integration Integrated Decision/Engineering Aid) system.

BACKGROUND

The Navy combatant ship constitutes one of the most complex weapon systems in a country's defense arsenal. It is a multipersonnel system conducting multiple operations (air, shore bombardment, warfare operations, search and rescue, etc.) in multiple warfare environments (antiair warfare or AAW, antisubmarine warfare or ASW, antisurface warfare or ASUW, electronic warfare or EW, and strike warfare), as an independent

combatant, a member of a squadron, or an element of a battle force. The ship systems employed in the fleet today, and those being designed for the fleet tomorrow, make severe demands on the readiness, performance effectiveness, and physical capabilities of the personnel who must operate and maintain them. These systems are complex, highly sophisticated, and extremely demanding of the sensory, motor, and cognitive skills and decision-making capabilities of system personnel.

The operational environment of the next generation of combatant ships will impose extreme information loads on the humans responsible for managing, operating, maintaining, and supporting shipboard systems. The variety and interactive complexity of systems, equipment, and personnel in the ship environment, coupled with requirements for rapid planning, scheduling, and deployment of mission elements within a dynamic, unpredictable threat environment, will converge to impose an untenable workload on the human operator. Cognitive workload will continue to be particularly high for ship personnel due to a variety of interdependent elements, including increases in the number and rate of decisions, as well as increases in the complexity and quantity of data that must be processed in order to make those decisions. Traditionally, such increases in workload have been compensated for by commensurate increases in the number of personnel; however, current and projected budgetary constraints, coupled with demographic data projecting a continuing reduction of military-aged males over the next twenty years, reduce the feasibility of this solution. The requirement to reduce manning levels as compared with preceding systems is becoming a fact of life for military systems in general. Projected defense department budgets demonstrate a definite trend toward reducing the numbers of personnel available to operate emerging military systems.

In addressing the issue of performing system functions with fewer human operators and maintainers as compared with existing systems, the function allocation strategy is not simply to assign functions to automated or manual performance on the basis of the different capabilities and capacities of the two, as exemplified in the Fitts' List approach. Rather, the strategy is to automate functions to the extent necessary to enable the required reduction in personnel, with attendant provisions for decision aiding, task simplification, and design in conformity with human factors engineering standards to ensure adequate levels of human performance.

In dealing with human-computer systems, it is also important to realize that the issue is not so much defining the allocation of system functions or tasks to human or machine performance as it is establishing the role of the human in the system. In a human-machine system where both components are equally competent to perform individual functions and tasks, the design issue is to determine the role of the human vs. automation in the performance of each function or task. The emphasis on the role of the human in the system acknowledges the fact that the human has some role in every system function or task. In some cases, that role may encompass actual performance of the function or task.

It is also important to realize that an assigned role for human performance may change with changes in operational conditions. Thus, a task performed optimally by a human under certain conditions of workload, time constraints, or task priority may be performed more optimally by machine under other conditions. It is also important to keep in mind that automating a function or task does not logically mean that the human does not have a role, that he or she has effectively been designed out of the system for that specific function or task. Rather, in an automated function or task, the role of the human is that of a manager, monitor, decision maker, system integrator, or backup performer.

Historically, the most frequently applied method to reduce manning levels has been to automate operator tasks, thereby reducing operator workload and manning requirements. Human-systems integration (HSI) generally attempts to reduce manning levels by automating specific tasks and establishing the potential for reallocating human tasks to automation, or redistributing human tasks to other humans. High-driver tasks are investigated to determine the potential for reallocating the task or task sequence to automated performance or to another operator. Analyses are conducted to assess the effect of reallocation of tasks on individual operator workload and on the potential for manning reduction. Techniques to reduce manning levels through training have also focused on redistribution of tasks among crew members. High-driver tasks are examined to determine the potential for cross training and organic, on-board training.

Attempts to reduce manning levels through consolidation of operating positions have been only marginally successful. This lack of success has resulted from two main obstacles: (1) specialized skills and knowledge required for different operating positions preclude simple

cross training; and (2) task performance for existing positions may involve critical activities that are parallel in time. Recent advances in the fields of artificial intelligence and HSI afford the capability to overcome these obstacles by providing on-line decision aiding, by enhancing cross training through organic training, and by allowing some measure of operators' specialized skills and knowledge to reside in the computer. This approach, which involves what are typically termed "expert systems," has met with considerable success in both commercial and government applications.

The underlying rationale of the HSI strategy for manning reduction involves the application of HSI techniques to reduce the physical and cognitive workloads imposed on ship personnel, permitting redistribution of workload among automation and human performance and among crew members, consolidation of existing operating positions, simplification of operator tasks, and reduction of overall manning levels. Application of HSI technology to reduce manning has been addressed formally only in recent years. The potential for reducing manning through improved task simplification and improved human-machine interface design has been demonstrated in a number of studies.

The critical issue in the HSI reduction of manning, then, is the relationship between manning and workload. The basis for predicting manning requirements must be the workload associated with the roles of humans in system operations. The problem, for the HSI specialist, lies in the measurement of workload. Workload measures and methods being sought involve human sensory, psychomotor, and cognitive capacities and the demands placed on these by operator tasks inherent in the design of ship systems. While workload measures in the area of physical work, muscular exertion, and physical fatigue are definitely of interest, the greatest uncertainty lies in defining workload in tasks that do not require much physical effort but, rather, load the operator in terms of perceptual, cognitive, and decision-making skills.

An obvious difficulty in measuring these capabilities and the demands created by system tasks is that the capabilities and the inferred workload are not observable. What is observable, however, and what ultimately contributes to or degrades total system performance, is operator task performance in terms of response speed and accuracy. The time taken to respond to stimulus events and the quantitative and/or qualitative accuracy of the response are measurable, at least in principle, and will influence total system performance.

Workload (or overload) is an intervening variable that must be inferred from observable performance. It is presumed, despite the elusive and indirect nature of the workload concept, that workload does exist and that the workload level imposed by a system task or sequence of tasks will influence task behavior.

REQUIREMENTS

Functions or tasks that are candidates for automation can be identified by determining the required role of the human in the system. The classical method for determining the role of the human in a complex system involves allocation of functions or tasks to human or machine (automated) performance. Function/task allocations can be either static or dynamic. Static allocations identify which functions or tasks should be allocated to human performance vs. machine performance based on an assessment of the requirements associated with the function/task and the unique capabilities and limitations of the human and the machine. Static allocations are usually made on the basis of lists (Fitts' lists) that compare the relative capabilities and limitations of human and machine performance along specific dimensions.

Dynamic allocations assume that the optimum allocation strategy can change with operational conditions, workloads, and mission priorities. According to Rouse (1977), a dynamic approach allocates a particular task to the decision maker (human or machine) who has the resources available at the moment for performing the task. Rouse (1981) identified the advantages of a dynamic approach over a static approach as: improved utilization of system resources; less variability of the human's workload; and provision of the human with improved knowledge of the overall system. Revesman and Greenstein (1983) recommended an approach in which the human and the computer work on tasks in parallel, with the computer selecting actions so as to minimize interference with the human. Here, the human is not forced to change planned actions and he or she retains the primary role in the system. In this implementation, the computer must make predictions about the human's actions and must, therefore, have a model of the human in terms of the actions the human will take at a given point and under certain circumstances. The computer would use this model of human decision making to predict the human's actions and to select other actions that do not replicate or interfere with the human's actions.

According to Woods (1985), the role of the human has shifted with increased control automation and developments in computational technologies. The shift is away from the perceptual-motor skills needed for direct manual control to cognitive skills of the type required to support roles such as monitor, planner, and fault manager. The key to effective application of computational technology is to conceive, model, design, and evaluate the joint human-machine cognitive system. The configuration or organization of the human and machine components is a critical determinant of the performance of the system as a whole. This means using computational technology to aid the user in the process of reaching a decision, not to make or recommend solutions. If joint cognitive system design is to be effective, models and data are needed that describe the critical factors for overall system performance (Woods, 1985).

METHODOLOGY

The major requirement imposed by the HSI initiative is that considerations for the human in the system, including manning levels, must influence system design. In order to influence design, attention to HSI requirements, again including manning, must begin early in the system development process. To have the maximum impact on design decisions, HSI requirements should be addressed prior to milestone 0, while mission needs are being determined, manning constraints are being specified, and alternate approaches are being considered. The most effective method for addressing HSI issues early in the development process is to focus on lessons learned in baseline comparison systems or predecessor systems. Lessons learned include problems identified in baseline comparison systems that should be avoided in the emerging system, as well as positive aspects of the baseline system that should be considered in the new system. Through the reengineering process, operations and tasks in existing systems that impose heavy workloads on humans can be identified, and requirements for alternative allocations can be specified. A second method for addressing human requirements and considerations early in system development is the use of computer simulation to model human performance in system missions and operations.

The HSI approach to influencing system design early in system acquisition, with special emphasis on reduction of manning in the emerging system, uses a four-step process to address the issue of establishing the optimum role of the human. These steps are: (1) identifying candi-

date roles of the human; (2) identifying specific requirements associated with these roles for specific scenarios; (3) modelling expected human performance in the set of assigned roles for the scenarios; and (4) assessing the alternative concepts of the role of the human in terms of their effectiveness, affordability, and risk reduction.

- Identifying candidate roles for the humans.

  In identifying candidate roles for the human in the system, the emphasis, from a reduced manning perspective, is to automate tasks that are currently performed manually. Identifying manpower determination lessons learned in baseline comparison systems involves assessing the adequacy of the allocation of functions to human or machine performance in these systems, and identifying where human functions and tasks can be reallocated to automated performance. This assessment requires a reverse engineering of the function allocation approach underlying the design concept implemented in the baseline or existing system. Through the reverse engineering technique, the rationale for allocation decisions can be made explicit and opportunities for alternate allocations can be explored. Alternative concepts of the role of the human involve alternate approaches to automation, decision aiding to reduce human workload, and improved design of human-machine interfaces to simplify tasks and reduce workloads.

- Identifying specific requirements associated with candidate human roles.

  The requirements associated with specific function allocation/role-of-the-human concepts include task requirements (information, performance capabilities, decision and support requirements, task sequencing, and time dimensions of tasks), human knowledge/skill requirements, and requirements for containing human errors. These requirements are generated for specific mission scenarios that represent configurations of mission objectives, threat and own force deployment, system readiness, and special conditions (environmental, operational, and tactical).

- Modelling human performance.

  For the task sequences and associated requirements defined for specific mission scenarios, human performance must be modelled to identify potential problem areas. The modelling process is twofold.

First, a task performance model is developed through application of task analysis. When task sequences and requirements are sufficiently well understood, a task network simulation is conducted to assess the impact of the specific function allocation or role given to the human on human performance and workload.

- Assessing alternative concepts of the role of the human.

  The HSI appraisal of function allocation/role-of-the-human concepts will include an assessment of technological requirements associated with the concept, and, for individual concepts, assessment of effectiveness, affordability and risk. The technology assessment will focus on the extent to which technological advancements are needed to support implementation of a specific concept. The assessment of concept effectiveness will address the extent to which the concept meets system requirements and will enhance system operability, usability, maintainability, support-ability, survivability, and safety.

The assessment of concept affordability will determine the extent to which life-cycle resource requirements are met for operational manpower, maintenance personnel, training, personnel nonavailability due to accident, expected human error rates, expected time to repair, supportability, and expected system down time. The assessment of risk for alternative function allocation/role-of-the-human concepts involves a determination of critical factors that will have a significant impact on, and carry risks for, readiness, life-cycle costs, schedule, performance, or design. These include such items as: tasks, task sequences, and task complexity; environments and environmental controls; equipment design features; maintenance requirements; information requirements; manning requirements and associated workloads; personnel skill levels and training requirements; and potential existence of health and safety hazards.

REARM

A methodology is needed that will make it possible to assess the allocation of function strategy in an existing system through a reverse-engineering technique. This methodology should be automated as much as possible and should provide for effective interfacing with a simula-

tion methodology so the effects of specific function allocation schemes on workloads, and, consequently, on manning levels, can be determined.

One methodology for integrating the human into a complex system was developed by Carlow International for the US Army Human Research and Engineering Directorate (USAHRED), the Naval Sea Systems Command (NAVSEA), and the Space and Naval Warfare Systems Command (SPAWAR). This approach is known as the HSI IDEA (Integrated Decision/Engineering Aid) (Malone et al., 1992). A subset of the IDEA tools aimed at determining the roles of the human in a system to support reduced manning has been designated "REARM" (for Reverse Engineering Allocation of function methodology for Reduced Manning). REARM incorporates several of the tools available in the IDEA system, including the IDEA Lessons Learned Database (IDEAL), the Role-of-Man Analysis Tool (ROMAN), the NETWORK Tool for creating a graphic task network, the IDEA Task Analysis Tool (I-TASK), the IDEA Simulation for Workload Assessment and Modelling Tool (SIMWAM) for task network simulation, and the IDEA HSI Assessment Tool (ASSESS). The REARM methodology seeks to describe, through reverse engineering, the allocation of function strategy evident in an existing system, and the negative and positive aspects of the strategy. The relationships among the IDEA tools under REARM are depicted in Figure 11.1.

In the IDEA methodology, the existing system is described in the Lessons Learned Database (IDEAL). The implemented roles of the human are developed through application of an automated tool designated the Role-of-Man Analysis Tool (ROMAN). The IDEAL provides techniques to acquire, analyze, classify, prioritize, and store data on lessons learned describing problems as well as positive aspects of the function allocation scheme in the existing system.

ROMAN allows the analyst to import a set of functions or tasks and to assign roles to humans and automation in the performance of each function and task. As each function or task is presented to the analyst, a decision must be made regarding which component (human or machine) should be the performer of the function or task. When an assignment cannot be made readily, the analyst selects the tool's consultation feature. The tool then presents a series of questions in which the analyst is asked to scale some dimension of the task, operational conditions and environment, user capabilities, and mission priorities. Based on the analyst's responses, the tool recommends that the task be assigned to

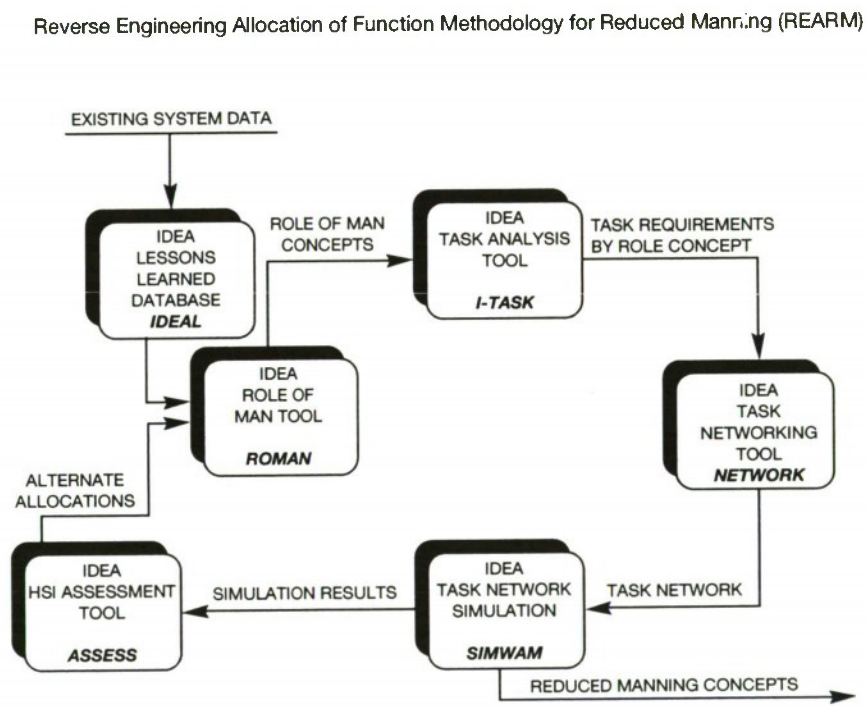

Figure 11.1. Relationship among IDEA tools for determining function allocation and the role of the human to achieve reduced manning.

human or machine performance. In each case where an assignment of task performance has been made, the analyst is asked to identify the role of the human and the role of the machine in the performance of the task.

The assigned roles for each task are then exported to the IDEA automated Task Analysis tool (I-TASK), where specific requirements for task performance are identified for each task under the specific allocation strategy and role assignments. I-TASK comprises a data bank of issues and concerns for human performance of system tasks as affected by the selected roles of the human and the machine in the completion of the tasks. For tasks that are cognitive in nature, either because of the task itself or because of the assigned role of the human in the performance of the task, the task data are exported to the IDEA Cognitive Task Analysis Tool (I-COG) for a refined analysis addressing the cognitive aspects of required human performance. The resulting task data are then imported back into the I-TASK Tool.

The results of the task analysis are then exported to the IDEA NETWORK Tool, which describes task sequences in a graphic flowchart format, with task descriptions available in text format. The task descriptions maintained in the NETWORK Tool comprise a subset of the requirements derived for each task in the I-TASK Tool. These task descriptions specify the performer of the task, the tasks that must precede the specific task, and the tasks that are dependent on the specific task; the role of the human in task performance if the human is not the performer; the estimated time required for task completion; and the process variables associated with performance of the task. Process variables include factors that have a bearing on task performance and that can vary for any simulation exercise. Process variables typically include capabilities or readiness of ship systems, operational/environmental conditions, mission data, and threat characteristics.

The NETWORK Tool runs on the Apple Macintosh computer and takes advantage of the Macintosh graphics capabilities and user interface to allow the analyst to draw a task network. A set of drawing tools is provided to generate, locate, and connect task boxes. A task box can be named and then opened to produce a set of dialogue windows. These windows allow the analyst to input details of a given task, including such things as the operator(s) qualified to perform the task, the priority of the task, conditions that must be met before the task can be started,

and parameters that specify the probability distribution of completion time for the task.

Once a task network has been defined, the data are exported to the IDEA simulation tool, SIMWAM (Simulation for Workload Assessment and Modelling) for simulation of the task network, exported to the I-TASK (task analysis) Tool, or exported to any of the Macintosh graphics applications for documentation purposes.

SIMWAM is a task network simulation tool that can execute a network model previously defined by NETWORK. SIMWAM allows an interactive, microprocessor-based simulation of human performance and workload. The objective of SIMWAM is to analyze a network of tasks that comprise the basis for determination of crew workloads, individual workloads, and personnel performance problems.

SIMWAM consists of a set of related programs that permit the analyst to: create and maintain a database of task requirements; execute the task network; print performance data following the network execution; and modify the task data to evaluate alternate concepts. Some of the features of SIMWAM that provide the resources for the analyst to model an existing or conceptual system include: predecessor relationships between tasks; calls for execution of other tasks on task completion; specification of the operator(s) qualified to perform each task; task interruption in case of operator assignment conflicts; task priorities that control operator assignment; and Monte Carlo sampling of task durations and task calls.

During a SIMWAM run, tasks are called when prior tasks are completed. If sufficient operators are available for a called task, it will be started. Input data describing a task include a list of qualified operators and the number of operators required to perform the task. In attempting to start a task, SIMWAM will assign capable operators who are currently idle. SIMWAM can also interrupt lower-priority tasks in process to obtain operators for higher-priority tasks. Operators are not necessarily human operators but could be any resource entity.

When a task is ready to start, SIMWAM draws a random sample from the probability distribution of duration for the task. While the task is in process, operator time is accumulated on the task. When the task is completed, it can call other tasks. If the call is probabilistic, then one task out of several will be called depending on specified probabilities. Human error, equipment failure, or a hit or miss following weapon firing are events that could be accommodated by probabilistic task calls.

A task can also call one or more tasks deterministically when a fixed sequence of tasks exists. Task calls can be made conditional on events or variable values by means of user-written subroutines. This capability ensures that virtually any logical conditions for the start of a task can be accommodated. For example, tasks required to process objects in a queue could be called only if there is one or more object(s) in the queue. As SIMWAM executes a network model, it tracks mission time, task completions, task start and end times, time spent per task per operator, and operator utilization (sequence of events showing task times and operators; summary of task completions and operator time on each task; matrix of the time spent on each task for each operator; and summary of active and idle times for each operator). At the end of a simulated mission, these data can be printed. At the end of a simulation run involving a number of missions, the means and standard deviations of mission data over the number of missions run can be printed.

The interactive nature of SIMWAM allows the analyst to evaluate alternate system designs or modifications involving manpower reduction, cross training, automation, task modification, or function allocation. SIMWAM has been used in several military applications to identify the potential for reducing system workloads and manning levels.

The results of the SIMWAM simulation exercise, in terms of workload and expected human performance problems, are provided to the HSI Assessment Tool, ASSESS. This tool supports an assessment of alternative role-of-the-human concepts in terms of affordability, risk reduction, and expected effectiveness. The affordability assessment addresses the extent to which affordability objectives are achieved with alternative approaches. Affordability objectives from an HSI perspective should address the cost risks identified for each alternative. The objectives should encompass reduced acquisition costs and reduced life-cycle costs. Reduced acquisition costs include cost reductions achieved through the integration of human factors engineering, manpower/ personnel/training (MPT), and safety and health design considerations, as well as a reduced need to redesign. Reduced life-cycle costs are achieved through reductions in: manning, training time, career progression "pipelines," requirements for new training facilities, accident rates, human error rates, time to repair, supportability requirements, system down time, and personnel nonavailability.

The HSI risk assessment addresses cost, schedule, and design risks associated with the role-of-the-human concept. Current human-system

cost drivers, MPT drivers, human performance drivers, and safety high drivers are identified for each concept, and trade-off decisions are delineated. Critical human-system factors are identified in design alternatives that will have a significant impact on readiness, life-cycle costs, schedule, or performance. These factors include: tasks, task sequences, and task complexity; environments and environmental controls; equipment design features; maintenance requirements; information requirements; user-computer interface features; manning requirements; workloads; personnel skill levels; training requirements; and health and safety hazards. Subsystems or components associated with each role-of-the-human concept will be evaluated for high or moderate risks.

The assessment of the effectiveness of each role-of-the-human concept begins with an analysis of outstanding HSI issues and concerns from each HSI domain. The relative criticality of each issue or concern identified is established. Finally, recommendations are formulated concerning the changes that could be made to a concept to improve its effectiveness.

After the HSI Assessment Tool is applied, the results of the assessments and any recommended changes to a role-of-the-human concept are then fed back to the ROMAN Tool for analysis and evaluation.

APPLICATIONS

The techniques and tools described above have been implemented in several HSI attempts to reduce manning in Navy systems.

REDUCTION OF MANNING IN AIRCRAFT CARRIER (CV) AIR MANAGEMENT

A study conducted for NAVSEA by Carlow International (Malone et al., 1986) involved the application of decision-aiding techniques in the form of automated status boards to reduce the manning levels of aircraft carrier (CV) aircraft management systems. This effort also resulted in the development of the workload simulation tool SIMWAM for measurement of the impact of human factors engineering design changes on system manning. The CV aircraft management system includes thirty-five operators. A scenario for exercise of this system was developed, with emphasis on the variables affecting human performance, for a sequence involving twelve aircraft launches and thirteen recoveries.

A SIMWAM simulation was conducted for a scenario currently implemented in the fleet. After tasks, sequences, and times to perform were verified in a ship visit (USS *Constellation*), the simulation was completed for the baseline condition. The sequences inherent in the network of tasks were then adjusted to reflect changes due to the introduction of automated status boards (ASTABs) as decision-aiding devices, and a second simulation run was completed with the ASTAB aids in place. The complete array of tasks performed by all operators was analyzed prior to conducting the second SIMWAM run with ASTABs included.

A comparison was made of the operator's active time with and without ASTABs. The results of this comparison indicated that four operator positions could be eliminated due to the reduction in workload following introduction of the ASTAB aid. Results also indicated that twenty-five of the remaining thirty-one operators were able to accomplish assigned aircraft management tasks in less time with the ASTAB than without it. This finding is statistically significant at beyond the .001 level. As for the magnitude of the time change from run 1 (without ASTAB) to run 2 (with ASTAB), it was found that, on the average, operators completed assigned tasks in run 2 in 20.6 percent less time as compared with run 1.

REDUCTION OF MANNING IN NEW ATTACK SUBMARINE SHIP CONTROL

Carlow International also recently conducted an effort for NAVSEA to reduce manning levels for the New Attack Submarine (NAS) ship control system. The thrust of this task was twofold: (a) to apply HSI methods and data to resolve whether ship control tasks could be conducted adequately under representative scenarios with two operators rather than four operators as in the baseline Seawolf system; and (b) to determine operator workloads associated with the reduced manning.

A description of the baseline ship control system (Seawolf) was developed that included: the roles and responsibilities of the four operators and other crew members involved in system operations (e.g., officer of the deck); the allocation of control function and authority to human control, semiautomated control, or fully automated control; the workstations provided to each operator and the human-machine interface fea-

tures associated with each workstation; and time estimates or constraints associated with specific tasks and task sequences.

NAS normal and contingency missions, conditions, and operations were identified and were used in scenarios to assess alternative automation concepts. A task sequence was developed for the baseline system for selected scenarios using the IDEA NETWORK Tool. Parameters associated with each operator task were identified based on inputs from subject-matter experts. Parameters include maximum and minimum time to perform tasks, task dependencies, and the effects of continuous operations on performance.

Workloads associated with Seawolf operators for each scenario were assessed using SIMWAM. Operators included those performing the functions of helm/planes watch, ballast control, diving officer of the watch, chief of the watch, and officer of the deck.

Feasible alternative approaches for reduced-manning ship control were then identified using the concepts already developed in the description of alternate ship control system design approaches. The roles of humans in the alternate automation concepts were determined using the IDEA ROMAN Tool. Task sequences for each ship control station automation concept were established for selected scenarios for the two ship control operators and all other personnel involved in ship control activities (e.g., the officer of the deck), and levels of specific task parameters were identified using IDEA NETWORK. Workload and performance assessments for each alternative concept were conducted using IDEA SIMWAM. Feasible concepts were evaluated using the IDEA HSI Assessment Tool to conduct assessments of (a) alternative concept effectiveness (operability, usability, maintainability, safety/survivability, and supportability); and (b) risk potential associated with each concept, including design risks, cost risks, schedule risks, and technology risks.

REDUCTION OF MANNING IN ADVANCED SEALIFT SHIPS

Carlow International is currently supporting NAVSEA (SEA 03D7) in the application of IDEA tools to reduce manning and improve the HSI aspects of Fast Sealift ships. A major contributor to the overall effectiveness of Sealift ships, systems, and missions is the performance and readiness of the Sealift ship crew. The HSI initiative addresses personnel requirements in Sealift ship design. The driving objective of HSI is to *influence design* with regard to personnel requirements and con-

siderations. This is achieved through an approach that, as described above, ensures that personnel considerations are addressed early in system development, that emphasizes attention to the role of the human vs. automation in system operation and maintenance, and that uses simulation to model human performance and workload.

Ancillary objectives of HSI as applied to the Sealift program are:

(a) reduced personnel requirements as compared with baseline systems;

(b) improved readiness of Sealift ships due to reduced skill requirements, reduced workloads, and task simplification;

(c) improved reliability of Sealift ships and ship systems due to an emphasis on software and a reduction of human error rates;

(d) improved personnel availability and survivability due to reduced hazards and accidents;

(e) enhanced system and equipment availability through reductions in time to repair; and

(f) enhanced system affordability through a reduction in personnel support costs, training costs, costs of systems unavailability, costs of human errors, and costs of accidents.

Activities to be accomplished in the effort include: developing a lessons learned database; tracking HSI issues in existing Sealift ships; identifying roles of humans and automation in selected Sealift mission scenarios; conducting function and task analyses for selected role-of-the-human concepts; identifying alternate approaches to reducing manning levels in specific Sealift systems; determining requirements to modify licensing procedures; determining training requirements; conducting HSI assessments; and conducting HSI and reliability analyses.

The specific requirements and constraints to be addressed in applying HSI technology to the Future Technology Variant Fast Sealift ship acquisition include the following:

- high-reliability equipment, which will result in a reduced need for a human backup capability, and at the same time will reduce the maintenance burden and the workload imposed on maintenance personnel;
- training pipelines that will assure ready availability of trained personnel in the numbers and time frame required while minimizing the time to complete training;

- reduced shipboard manning levels that address reduction of workload by automating tasks currently performed manually and moving to shore establishments activities currently performed on board, as well as applying HSI technology such as decision-support systems, job performance aids, task simplification techniques, and on-line intelligent tutoring;
- reduced skills required to perform tasks in a reduced manning environment, through application of HSI technology such as decision-support systems, job performance aids, task simplification techniques, and on-line intelligent tutoring;
- personnel career progression and advancement;
- integration and consolidation of rates and ratings that will result from reduced manning;
- emphasis on influencing design based on a ship, system, and equipment design philosophy that envisions the role of the human as decision maker, systems manager, and overall supervisor, and the role of the machine as encompassing that of worker;
- focus on total ship as well as ship system and equipment acquisition, as opposed to ship system/equipment acquisition alone;
- emphasis on user acceptance, with the user viewed as encompassing the military organization responsible for Sealift operations, the commercial ship owner/operator, and the on-board human operator and maintainer;
- integration of HSI technology into ship and system acquisition through implementation of a standardized and formalized HSI process that is itself an application of the systems engineering approach.

The application of HSI to the Sealift Future Technology Variant program will be accomplished over a three-year period. The products of the effort that will be available at the end of this three-year period are as follows:

(1) HSI issues and constraints for the Sealift program;

(2) ship operational procedures for reduced manning levels;

(3) results of HSI technology, effectiveness, affordability, and risk assessments;

(4) training requirements based on existing licensing procedures;

(5) reduced manning concepts for electric systems, propulsion systems, auxiliary machinery, ship control, and ship services such as food service; existing Sealift ships require manning levels of thirty to forty persons; the goal in HSI application is to reduce manning levels to twelve to fifteen people, for a manning reduction of up to 70 percent;

(6) ergonomic design of integrated consoles for single operators for electric and propulsion systems, auxiliary machinery, and ship control;

(7) innovative messing, inventory control, and stowage concepts;

(8) strategies to effect revised US Coast Guard (USCG) regulations, and requirements to revise USCG regulations and to accommodate union requirements;

(9) requirements for curriculum changes and a model curriculum for reduced-manning ships;

(10) final requirements to revise USCG regulations;

(11) validation of reduced manning and manpower determination processes and tools.

REFERENCES

Malone, T. B., Heasly, C. C., Kirkpatrick, M., Perse, R. M., Welch, D. L., Perse, R. M., Vingelis, D. P., & Westerman, P. J. (1992). *The US Army Human Engineering Laboratory's HFE/MANPRINT IDEA; Integrated Decision/Engineering Aid* (Final Report). Falls Church, VA: Carlow International.

Malone, T. B., Kirkpatrick, M., & Kopp, W. (1986). Human factors engineering impact on system workload and manning levels. In *Proceedings of the Human Factors Society 30th Annual Meeting* (pp. 763-767). Santa Monica, CA: Human Factors Society.

Revesman, M. E., & Greenstein, J. S. (1983). Application of a model of human decision making for human/computer communication. In *CHI83 Proceedings*. New York: Association for Computing Machinery.

Rouse, W. B. (1977). Human-computer interaction in multi-task situations. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-7, 5.*

Rouse, W. B. (1981). Human-computer interaction in the control of dynamic systems. *Computing Surveys, 13*(1), 71-99.

Woods, D. D. (1985). Cognitive Technologies: The design of joint human-machine cognitive systems. *AI Magazine.*

12

MANAGEMENT OF FUNCTION ALLOCATION DURING PROJECT DEVELOPMENT

P. Aymar

In function allocation, as in any other human factors technique, there are many unanswered questions. Partial answers do exist, however, and can be useful for system design, provided they are compatible with the logic of project management. This paper offers some guidelines by describing how human factors can be managed in a project. The main steps in project management are: definition of a project strategy, specification, concept development, and evaluation. The need for techniques to simulate different schemes of task/function allocation is pointed out.

INTRODUCTION

Function allocation is a proven software development methodology. Transposing it to hardware or human-machine interface development is not as easy as one would expect, however. While computer memory can be nearly infinite and accommodate multiplication of modules, the real world is finite; a workstation has a limited number of slots, and obviously a human has a limited number of fingers, arms, and cognitive abilities as well. This paper provides a few hints for exploring how the concept of function allocation translates to human factors, using management as a guideline.

Project management is a process that ensures that a satisfactory prod-

uct will be delivered at an acceptable cost and schedule. It relies on four main steps:

- definition of a strategy based on risk management considerations;
- specification of what has to be done;
- concept development;
- control of the concept development process and products.

The main management tools are the functional specification, the technical specification, and the evaluation program.

For each of these steps, the initial phases of the program are crucial (this is where 10 percent of the money is spent, and 90 percent of the choices are committed). In these phases, the only representations of the project available are some futuristic concepts used to justify funding, the functional description, and occasionally some mock-ups. The functional description is the only one with contractual relevance. The "functional" approach thus has special importance because it forms the basis for a common language for development and for the evaluation of the deliverables; it includes all the cases of the word, such as "function allocation."

PROJECT STRATEGY

The project manager's task is to handle risks, which may come from management, technique, operation, etc. Risk management is a discipline in itself with its own experts. From a human factors standpoint, however, the basic considerations include:

- level of detail of the specification;
- methods and tools mandated;
- control level and communication support;
- coordination/cooperation among project actors.

The last item is the most crucial. Paradoxically, it is human factors people who suffer most when there are deficiencies in this human factors element. One strategy can be to set up human factors databases providing a common and validated view of the project. *Fiches operateurs* and *fiches equipement* are used for this purpose in France. Nev-

ertheless, a common understanding of human factors objectives is necessary.

One formulation of such an objective is to make the system and its various subsystems usable; for instance, if we consider a ship, it must be usable by:

• The Navy	through	- Human resources management - Training
• The crew and work teams	through	- Organization of collective activities - Communications - Habitability and living conditions
• Individual operators	through	- Operability of systems - Work conditions

The knowledge required can be summarized by citing the domains for MANPRINT (Manpower and Personnel Integration program):

- human factors engineering;
- manpower;
- personnel;
- training;
- system safety;
- health hazards;
- basic methods.

MANPRINT suggests a way to implement human factors by organizing the debate around the use of the system (the "how"), because this is where technical people and human factors people meet. Different points of view exist in a program (see Figure 12.1). The problem is to organize cooperation among the groups with these different perspectives.

Figure 12.1. Viewpoints in a system development program.

For instance, on a C^3I system:

• Architects	think about	- Technical objects (hardware)
• Programmers	think about	- Functional objects (software)
• Users	think about	- Operating/operable objects (liveware)

An implementation program that would allow these actors to communicate can be structured as shown in Figure 12.2.

The human factors expert or the project manager would then ensure the execution of the program, providing expert advice centered on the work activity.

SPECIFICATION

Specifications can be functional or technical, depending on the intended point of application in the design process. Specifications are developed through the elaboration of functional concepts and design information. In a top-down approach, functional analysis must be supported by detailed technical information. Information must be compiled from various sources, which may include the results of an analysis of current systems, mock-ups, prototypes, or prospective or equivalent systems. This synthesis of tasks and activities helps to organize a negotiation between operator-oriented and technical-oriented segments of the work organization.

The following is an example of a discussion that might ensue:

Human resources representative: "I prefer to keep the old system because the operators are *trained to use it.*"

Technical representative: "Yes. But, as you can see, *operations* are much simpler with this system, so you need less people."

Human resources representative: "I understand. It would suit us better if you *transfer this task* to the operator, so that we are sure he won't lose his skills." ...

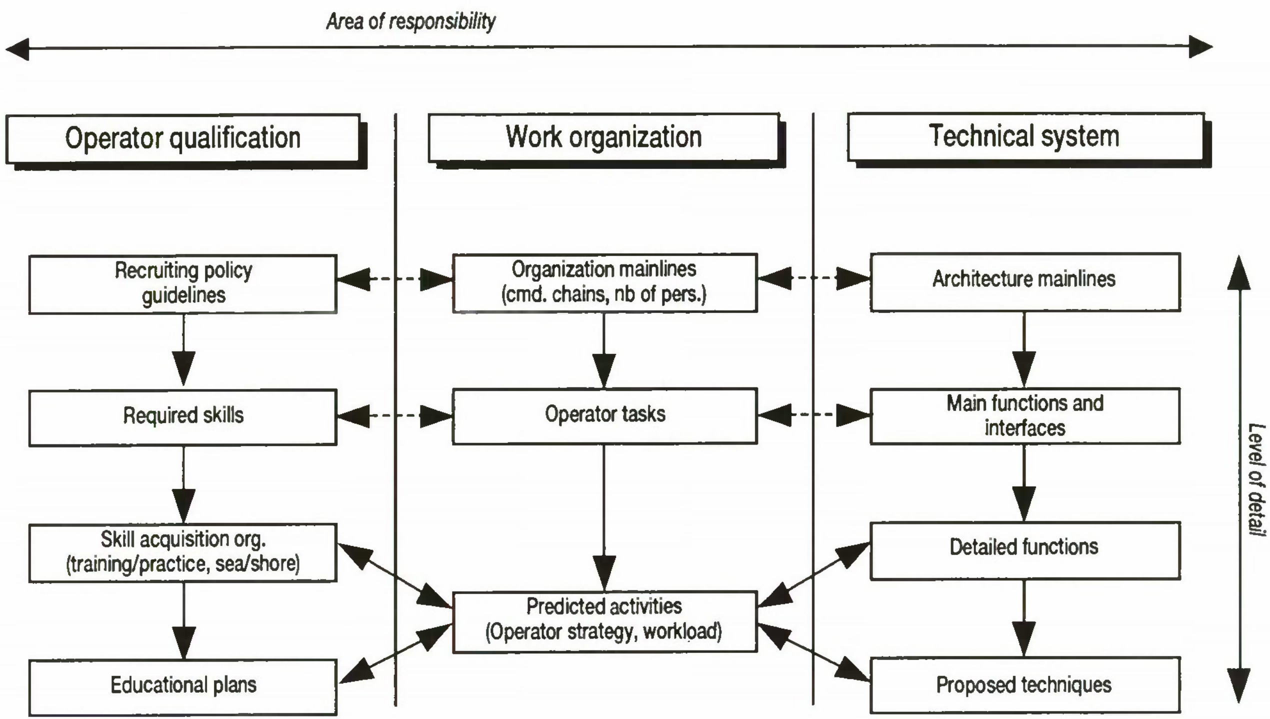

Figure 12.2. Communication between areas of responsibility. A horizontal arrow represents the communication and control process (consistency checks, for example). A vertical arrow represents the application of methods and tools.

The synthesis process could be illustrated as follows:

In major projects, such as building a ship, there are many subcontractors. The specification is not only a system description, it also forms the basis for the contract allocation with all its constraints: evaluation, design responsibilities, and money. These contract-sharing considerations quite often dominate, because they reflect industrial know-how and market reality (which has always had a strong influence in NATO countries). However, contract allocation always has a strong impact on either function allocation or integration. In both cases, the choices have consequences for the future operator. They will sometimes influence the homogeneity of human-machine interfaces. They can also determine which organization will support the operator in such areas as training, career management, selection, ranks, and grouping. The process of function allocation increasingly takes into account the consequences of such choices on the operability of the future system. Distributed models (MicroSAINT, etc.) help in considering these factors. It would also be useful, however, to integrate a wider range of human factors considerations, for example, skill acquisition—and why not also include job satisfaction and personal achievement?

CONCEPT DEVELOPMENT

Concept development is usually the obscure phase of structured top-down approaches such as those induced by functional analysis. Innovation is not consistent with function allocation, which encounters an intrinsic difficulty at this stage: the next step should be to allocate functions to the design objects. But which objects? What is needed is iteration with a bottom-up approach in which candidate objects can be selected. The selection of objects would be more accurate, while the functional chunks would become larger and more structured. So far so good, and this is globally the scheme used by my fellow engineers. This process, however, tends to ignore the synergistic/antisynergistic properties of systems and the possible benefits of redundancies.

There is a constant need throughout the project to:

- structuralize functions;
- evaluate the impact of different conceptions on the integrated system.

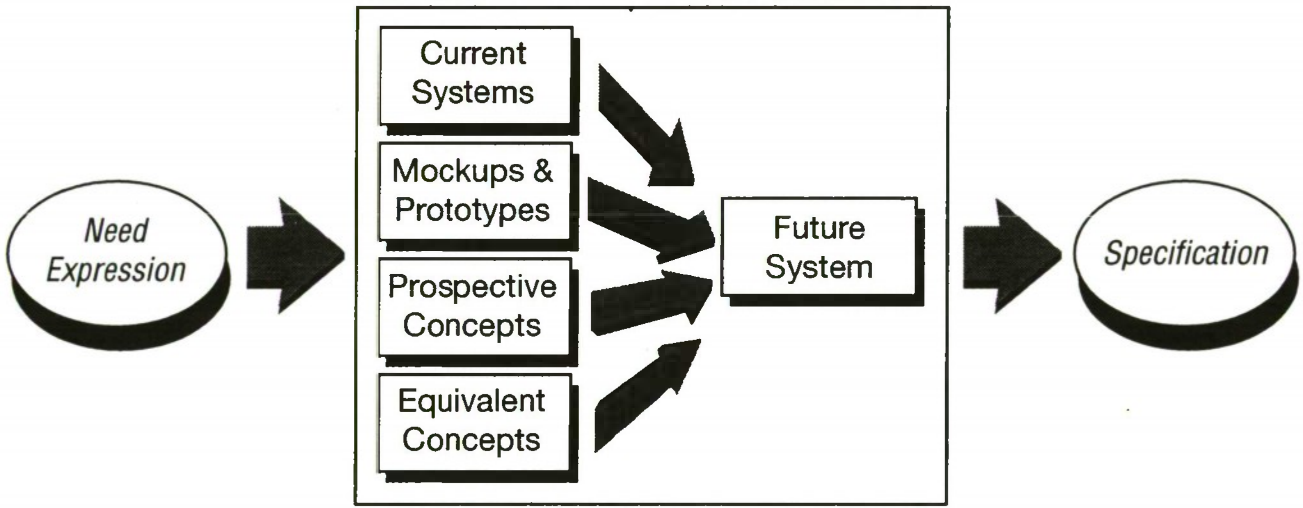

Figure 12.3. The synthesis process from need to specification.

There are many analysis methodologies (object oriented, Petri, semantic, cognitive, etc.). They offer alternative perspectives of the system: What is it used for? In what state is it? What is it doing? What information does it use? They help to structure system functions according to the reference chosen. At the other end, prototypes and integration platforms help to represent the function, its technical implementation, and the user, in their working environment.

EVALUATION

The evaluation process continues throughout the project. Evaluation matrices are available, and quite a few are found in the literature. Every human factor expert has his or her own, depending on background (e.g., nuclear, C^3I, aircraft). The job of the manager is to define the matrix most appropriate to the given system, and to quality and risk management objectives. Then the manager needs to implement an evaluation plan that will help in controlling the work and deliveries of the subcontractors. Basic evaluation methodology includes verification of compliance with standards, operability checks, and user trials. The following is an example of a matrix for evaluating warship systems:

- Operability
  Human-machine interface devices
  Workstation facilities
  Help devices
- Teamwork
  Operator role
  Workload
  Communication
- Work conditions
  Layout
  Environment
  Hygiene
  Security
- Human resources requirements
  Number
  Selection
  Training

Evaluation should occur at all stages of development of the system. User trials of prototypes and mock-ups should be scheduled to address the human factors issues listed above. Before mock-ups or prototypes have been produced—for example, in the concept development and design stages—the only things to evaluate are the functional description of the system and the suitability of the proposed technical solution with respect to required overall performance. Modeling of the distributed system, when it is carried out with enough methodological and experimental care, is a way to validate such virtual systems. The function allocation itself, including all its implications for the operation of the system, should be evaluated. This may include human-machine interaction, task redundancies, and allocation of tasks among operators. The evaluation should take into account external data such as use scenarios, performance, and reliability of imposed concepts of equipment and organization.

CONCLUSIONS

Function allocation is more than a design feature, it is a major concern to project management. Function allocation should be:

- a specification tool;
- a basis for contract allocation and evaluation;
- a tool for communication and dialogue among project actors.

It can also be a design tool extending the top-down approach to the definition of the physical or visual subsystems of the human-machine interface. Function allocation must also be reliable, and methodologies should include evaluation and performance indicators.

With adequate support and management tools such as human factors planning and supervision, a project manager is able to integrate human factors into the course of work. Function allocation would then play an important part in this process; but the consequences of each function allocation alternative on future activity need to be made clear. The challenge, of course, is to include human factors engineering considerations such as the operability and habitability of the system. Techniques like modeling, CAD/CAM, and scale 1 mock-up offer fair support in such endeavors. A wider range of human factors issues also needs to be considered, however, such as teamwork and integration into the user's organization (the Navy in the case of ships). The latter offers the toughest

challenge but also the greatest rewards; it will show the rationality and cost-effectiveness of considering factors like skill acquisition, job satisfaction, and personal achievement.

REFERENCES

Booher, H. R. (Ed.). (1990). *MANPRINT: An approach to systems integration*. New York: Van Nostrand Reinhold.

Délégation Général a l'Armament. (1991). *Méthodes de management de programme* (DGA AQ 902). Paris: Ministère de la défence.

Délégation Général a l'Armament. (1994) *Facteurs humains dans les programmes d'armement. Guide pour la prise en compte de l'ergonomie* (DGA AQ 913). Paris: Ministère de la défence.

13

FUNCTION ALLOCATION TRADE-OFFS: A WORKLOAD DESIGN METHODOLOGY

M. L. Swartz and D. F. Wallace

It is well known that humans perform certain tasks better than machines and that machines perform other tasks better than humans. In systems design, however, allocation of tasks between human and machine is not straightforward. Tools and heuristics exist, but more robust function allocation tools are needed. The Workload Analysis Aid (WAA) of MAN-SEVAL (Manpower-Based System Evaluation Aid) can be used to model operator performance to facilitate function allocation trade-offs. The US Navy is using such technology to understand function allocation and workload relationships in tactical display design. Traditional engineering approaches often involve automating functions without regard to human factors and the operator's performance limits. This paper discusses a series of function allocation trade-off studies based on a human engineering analysis of operator performance. Results are presented in the context of operator workload with reference to display design solutions.

INTRODUCTION

Deciding how to allocate control of system functions in real-time, highly automated tactical environments that enable operators to perform optimally is essential to good human-engineered design. The NATO Sea Sparrow Missile System (NSSMS) is being redesigned to accommodate its integration into the Ship Self-Defense Program. The NSSMS is already highly automated, with semiautomatic modes of operation for

certain tactical situations. The current design, however, was not human-engineered to take into account operator performance requirements. To address this issue, we looked at human performance criteria and function allocation trade-offs in the NSSMS so that the redesigned human-system interface would: (1) follow human factors engineering design principles and (2) support optimal operator performance.

In the current design, NSSMS operators are faced with a host of tasks, each competing for attention during a mission. Two task conditions present workload problems for operators: electronic countermeasures (ECM) and LOCAL (manual) control of target acquisition functions. In an ECM environment, workload is increased because additional processing demands (e.g., monitoring an ECM scan for targets) are imposed on operators. LOCAL control functions are performed infrequently, but their impact on operator performance is high. This mode of operation in the current NSSMS design requires that operators manually control certain tasks (e.g., target search). LOCAL control under ECM conditions further compounds this workload and places the greatest demands on operators. Some functions that are not currently automated should be; others need to remain under operator control. This scenario presented the basis of our workload-based function allocation trade-offs.

NSSMS FUNCTIONS AND OPERATOR CONTROL

NSSMS radar sensors locate a target, automatically track it, and guide the missile to the target location when it is fired. The system is operated by two individuals. The firing officer's console (FOC) operator is responsible for supervising tracks, missile management, and launcher assignment data. The radar set console (RSC) operator also supervises some dynamic processes and is responsible for most ECM and LOCAL control tasks. Automatic computer control of NSSMS processes operates at high data rates to carry out specific system functions efficiently and accurately while the operators monitor these processes. The assumption for these "system supervisors" is that they sample the relevant information at a sufficient rate to make an appropriate intervention decision. The problem for the human operator, however, is twofold. First, we know from human-information-processing theory that humans have limited resource capacity in terms of the amount and type of information they can process. Second, operators can introduce noise into a system's

closed-loop feedback system if information is not sampled at adequate rates (Moray, 1986) or if simply the wrong information is processed.

For example, the RSC operator monitors system status data and assigned tracks during target tracking. As the operator supervises system processes, he or she may have to make a decision and interrupt the system control loop, such as in the case where target priorities change. In mission-critical situations, we can say the operator's workload for these tasks is high. Under ECM conditions, workload will increase even more. Often the RSC operator needs to assume manual control so that electronic counter-countermeasures (ECCM) can be taken. The operator's strategies for handling high workload may affect supervisory performance. The operator may not monitor processes effectively, may decide to change task order, or may even drop nonessential tasks.

An intuitive design solution for these potential errors may be to reallocate the tasks and monitored information more equitably between the two operational stations (RSC and FOC). This solution, however, cannot be accomplished adequately within the constraints of the existing system, or without analyzing the supervisory control aspects and their related information-processing requirements for both NSSMS operators. The reallocation of tasks is not straightforward (Sheridan, 1988). It must be based on sound human factors engineering principles for supervisory control paradigms and must be integrated within the system engineering design for the NSSMS. Incremental function reallocation trade-offs will provide an understanding of how workload is distributed across tasks and between operators when taking control of the autonomous control loops in NSSMS. This incremental analysis will also provide preliminary assessment of human resource requirements for the system as part of Ship Self-Defense when certain functions become automated that currently are not.

MULTIPLE-RESOURCE THEORY AND WORKLOAD

Multiple-resource theory (Wickens, 1986) provides a framework for describing the various resource channels that NSSMS operators utilize to perform mission tasks, and a means for assessing the total load upon the operator at any one time. This theory states that attention-processing resources are limited and must be allocated among all tasks performed by an individual. As workload increases, this limited capacity pool of resources may no longer be able to provide the attention and processing

needs for the task(s). Each resource channel (auditory, visual, cognitive, psychomotor) is viewed as a distinct processing system, so that an individual can be fully "loaded" on one channel when the full capacity of that channel is utilized (e.g., listening to a Doppler shift signature loads the auditory channel) yet still be able to undertake an additional load on other channels (e.g., reading range rate on the display loads the visual and cognitive channels) without performance decrement on either task.

Capacity limits for each channel can be defined by the number of "bits" of information that can be processed in any one of the four resource channels. This limit of 7±2 bits of information is well known in the experimental psychology community. Function allocation trade-offs based on an analysis of these capacity limits will enable us to design console displays that present information in ways that best support the operator and his/her cognitive capabilities.

We approached this display design problem by conducting a detailed analysis of operator performance that included: (1) an assessment of operator task requirements and workload; (2) a trade-off analysis of system functions to reallocate tasks among the appropriate number and type of operators, including automation; and (3) a design guideline report describing the necessary input devices and information displays to support NSSMS operators as supervisory controllers of system processes. This paper presents the results from task items 1 and 2.

STUDY DESIGN

We developed exemplar mission scenarios to identify realistic naval threats for ECM and LOCAL control conditions. We video-recorded these simulated scenarios with actual NSSMS operators at two Navy sites for subsequent analysis. Control conditions (no ECM and semiautomatic [no LOCAL] control) were also video-recorded and used as a workload baseline.

PARTICIPANTS

Naval personnel with NSSMS operations and/or training experience were recruited from naval bases in Oxnard, CA, and Chesapeake, VA. All participants had received training on NSSMS systems. Some of the participants were NSSMS instructors. The level of NSSMS operator

console experience ranged from 1 to 9 years; operators with actual combat experience were not available.

APPARATUS AND MATERIALS

Video cameras were used to capture operator performance during this study. All scenarios were generated using the NSSMS training simulator and were run on FOC and RSC consoles and other NSSMS hardware to ensure the validity of our findings. Paper-and-pencil questionnaires were also employed for the structured interviews. A human performance modelling tool, Workload Analysis Aid (WAA), which is a component of the Manpower-Based System Evaluation Aid (MAN-SEVAL) (Army Research Institute, 1992), was used to run simulations of the modeled NSSMS tasks and to conduct function reallocation trade-offs between automation and the human operators.

PROCEDURES

Videotaped Scenarios. All operators were informed as to the purposes of the study and provided informed consent to participate in this investigation. Operators were asked to perform a suite of representative NSSMS tactical engagement scenarios including operations in both ECM and non-ECM environments, semiautomatic and LOCAL operations, and prosecution of air and surface targets. All representative scenarios were run in real time, and operator actions were videotaped. The videotapes were time-stamped, and specific task times were calculated for each mission scenario.

Operator Interviews. After all scenarios were completed, operators were interviewed to assess the operational models used by the NSSMS operators and clarify any actions performed during the tactical simulation. The interviews were also used to elicit discussion of any difficulties operators have had in using the current system and any suggestions or "wish lists" operators might have for improvements, features, and enhancements to the display and console.

WAA Human Performance Models. Descriptive human performance models for both the FOC and RSC operators were built using the WAA tool. The videotaped scenarios were used to capture the true task performance and to provide task-time data. Each function and its constituent tasks were assigned the appropriate time. NSSMS experts assisted in the

verification of these models and time on task to ensure accuracy. Under each major function, tasks and subtasks were listed and organized into either serial or parallel sequencing with other tasks. Where mission-defined branching occurred, appropriate probabilities were assigned for each branch. Performance times and WAA-derived resource-channel values were also assigned for each task. Each model was run and the workload results analyzed. After a model was built and analyzed, the WAA tool permitted reallocation of tasks between operator and automation within a particular model. This capability was utilized to model performance in a suite of function allocation trade-offs.

RESULTS

Descriptive performance models were run for all study conditions (semiautomatic versus LOCAL, ECM versus no ECM). These models provide an objective description of task-analysis-derived performancc and are not to be construed as predictive models of operator behavior. All tasks under each condition were assigned with resource-channel values to identify the complexity of the tasks. Results plotted workload into histograms for each channel's loading per task. WAA also provided task-overload summary results for each simulation model. Duc to the varied nature of the ECM environment, multiple contingencies, and the fact that some of the activities are classified, we decided to model ECCM tasks in WAA as a continuous function, parallel within the other functions, that can occur at any time for up to the full duration of the coincident function. Thc ECCM workload values were modeled separately and a composite set of workload weightings derived. We set a limit for each channel of 7 bits to ensure the control of potential workload in the new design.

Each simulation run resulted in a total mission time of 4 minutes 42 seconds, well within the set limits of the defined mission time of 4 minutes 50 seconds (which includes 3 minutes for tuning the missilcs).

OVERALL WORKLOAD

Workload was highest during ECM for both operators as predicted. The RSC operator had greater workload in both LOCAL control and ECM conditions in general as compared to the FOC operator. The FOC operator had greater workload during certain functions in both condi-

tions, but this was due to added verbal communication tasks with C^2 personnel and normal state verification of console indicators, not real-time tactical demands incurred in either LOCAL control or ECM. The effects of overall workload for both NSSMS operators are illustrated in Figures 13.1 and 13.2. Here we show a simple additive model that sums the loads across all four channels. If, for example, each processing channel was loaded at 7 bits of information, the operator would be fully loaded at 28 (4 channels × 7 bits). This is not to assume that a value of 28 or less is acceptable, but rather to illustrate that any combined workloads of greater than 28 are excessive and cannot be sustained by an operator for any period of time.

Research suggests that specific workload channel overloading is not the only factor to be considered in examining operator performance (Huey & Wickens, 1993). Operators can sometimes cope with heavy workload in one channel by shifting tasks to other processing resources or eliminating tasks. If all channels are heavily loaded, the operator's coping options are reduced. Post-experiment interviews revealed that some operators used such coping strategies, but this type of analysis was not pursued further in this research.

SPECIFIC TASK AND CHANNEL LOADINGS

Next we discuss the specific tasks on which high workload occurs and the specific resource channels that are affected for each NSSMS operator. Since the worst-case scenario for workload is when the system is under LOCAL control in an ECM environment, this discussion will focus upon that condition.

An analysis of FOC operator workload revealed that the cognitive and visual channels are most often overloaded. Further analysis revealed that the majority of the visual overloads and many of the cognitive overloads were directly traceable to prescribed observations of system status indicators, as in both system readiness and target engagement tasks. Of the remaining overload conditions, our analysis showed that many of these were transient "spikes" of increased workload as opposed to a sustained workload over long periods of time. The particular functions with the most sustained workload are: target tracking (where missile management decisions are made), target engagement (firing of missile), and post-fire evaluation (determination of appropriate actions to perform

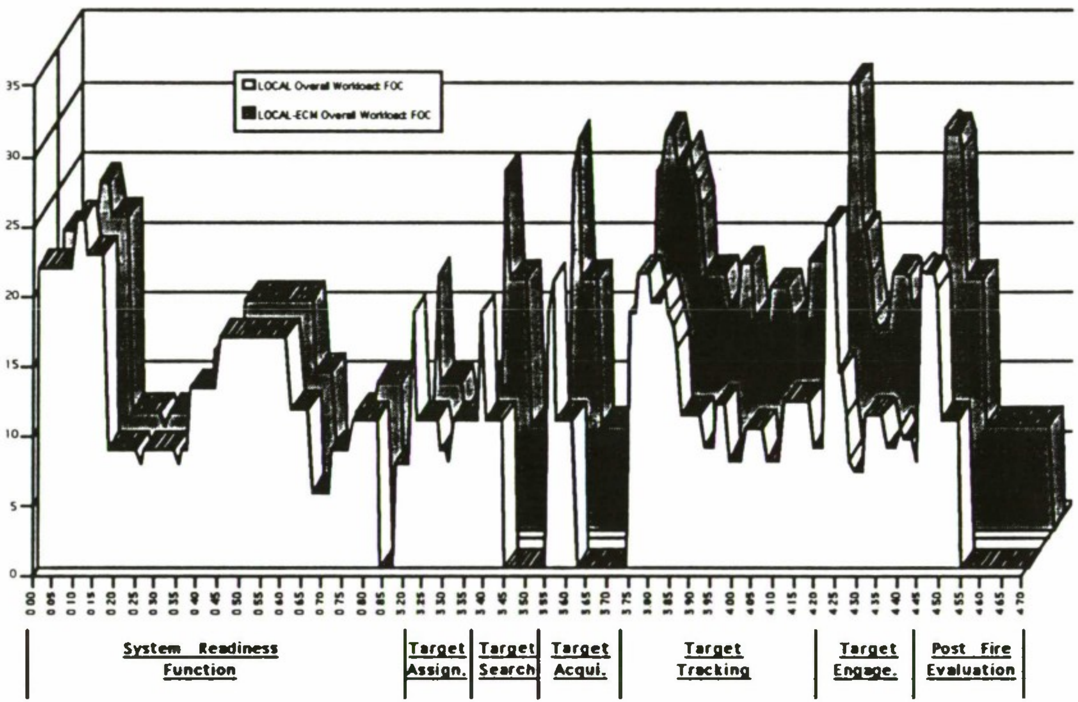

Figure 13.1. Firing officer's console (FOC) operator workload for LOCAL control, no ECM condition (white area) and LOCAL control, ECM condition (gray area). The x-axis depicts mission time and system functions; the y-axis, an additive scale of bits of information. Excessive workload is above 28, a combined total for the four individual channels assessed.

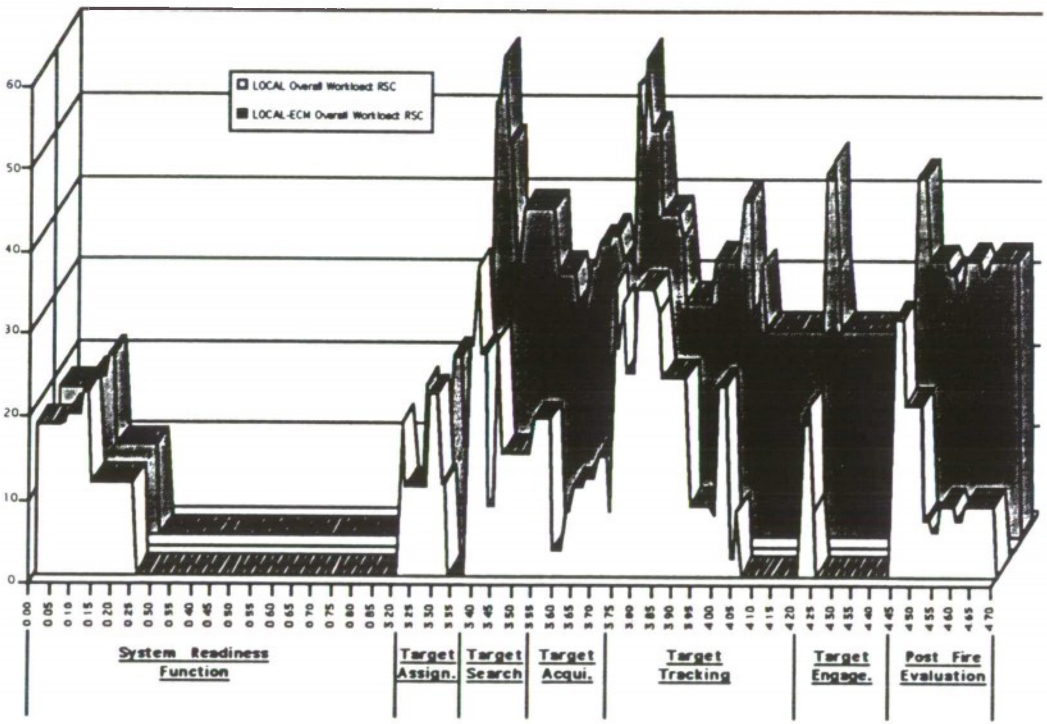

Figure 13.2. Radar set console (RSC) operator workload for LOCAL, no ECM condition (white area) and LOCAL, ECM condition (gray area). Same scale as for Figure 13.1.

based upon tactical situation, ship's doctrine, and engagement outcome).

A different pattern of workload was seen for the RSC operator. Again, the visual and cognitive channels were most often overloaded across tasks, but a substantial psychomotor load was also encountered occasionally during target tracking. Even the auditory channel was overloaded during target tracking when Doppler audio cues and speech (FOC-RSC communications) were processed simultaneously. As with the FOC operator, visual observation of normal system status indicators contributed to high workload. Unlike the FOC operator, however, the RSC operator is subjected to a more sustained, elevated workload. Some of the specific functions that contributed to prolonged extreme loading were: target search (where many visual and cognitive resources are demanded to identify target video returns), target acquisition (psychomotor demands for dual cursor controls, one rotary, one linear), target tracking under ECM conditions (visual and cognitive resources demanded to maintaining target return, identify ECM encountered, and counter ECM, all at the same time), and post-fire evaluation (kill/survive decisions).

TASK REALLOCATION TRADE-OFFS

Based on the above results, we ran a series of function allocation trade-offs using the WAA tool to reallocate selected tasks in the LOCAL control mode between the two NSSMS operators with different levels of additional NSSMS automation. We also examined a trade-off between a single NSSMS operator and additional NSSMS automation as a first step in identifying appropriate personnel levels for NSSMS operation in the new system design.

We ran the function allocation trade-offs with the LOCAL control/ECM models because task demands for this condition pose performance problems for operators during the stress of actual engagement. This was also confirmed in the results presented above. In addition, many LOCAL control/ECM tasks are not currently automated in the existing NSSMS design. Since the visual and cognitive channels were the two that are most highly loaded in these conditions, we were interested in reallocating tasks with those resource requirements. The WAA tool allowed us to reassign tasks and then run the simulations to model the redistributed tasks. Workload histograms were again plotted and thresh-

old levels assessed. In these trade-offs, as before, we used 7 bits of information as the maximum allowable limit for any one resource channel at any one time.

In the first trade-off, we assigned all of the system verification and monitoring tasks across all functions to automation. These visual tasks were unnecessary and accounted for a great deal of the excessive load for both operators. Our design work is looking at display methods that reduce these task demands through more efficient information presentation (Swartz & Wallace, 1994). This trade-off showed that, overall, both operators' workload was reduced as indicated in Figures 13.3 and 13.4. These levels are dramatically lower when compared to workload levels for the baseline allocation of tasks for LOCAL control/ECM conditions shown above in Figures 13.1 and 13.2. The system readiness function and all constituent tasks in this trade-off were below the 7-bit threshold for both operators. The FOC operator experienced a high workload spike in the target acquisition and post-fire evaluation functions. The RSC operator's workload began with the target search function as a high, discrete spike and then remained high through the rest of the mission.

Consistent with the previous workload results, the visual and cognitive resource channels continued to experience excessive workload despite these automation trade-offs. Clearly, more function allocations to automation are needed in order to reduce the load to more manageable levels.

Under the next function reallocation trade-off, we included increased automation of additional tasks for both operators based on some of the workload-reduction techniques we were developing for the new console displays. Examples include: (1) transformation of target data observations, mental conversions, and calculations from three separate display indicators to a single graphical display that automatically provides a synthesized result; and (2) redesign of more complex selection and motor tasks (e.g., determination and transfer of track to a target-launched weapon, or integration of bearing and range rate controls into a unified multiple-degree-of-freedom input device). These display solutions for the new NSSMS console design are described further elsewhere (Swartz & Wallace, 1994).

The results of the simulation run showed a dramatic drop in workload

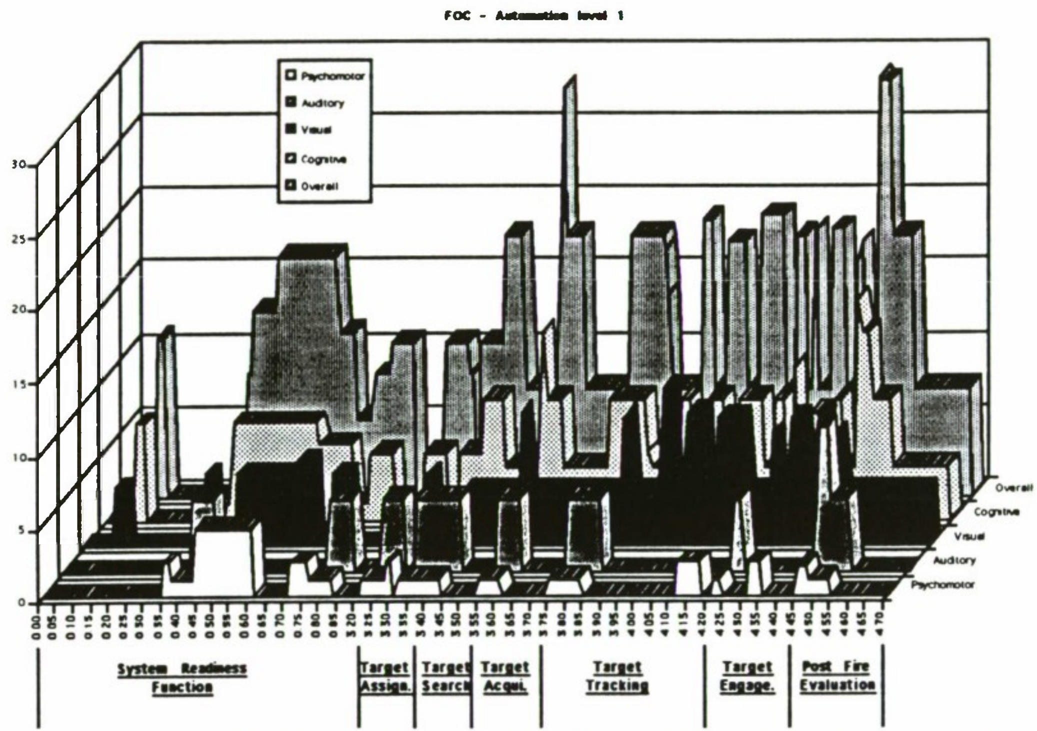

Figure 13.3. Channel workload levels for the FOC operator when a minimal function allocation trade-off is used. Excessive workload is reflected where workload exceeds 7 (bits) on an individual channel or 28 overall.

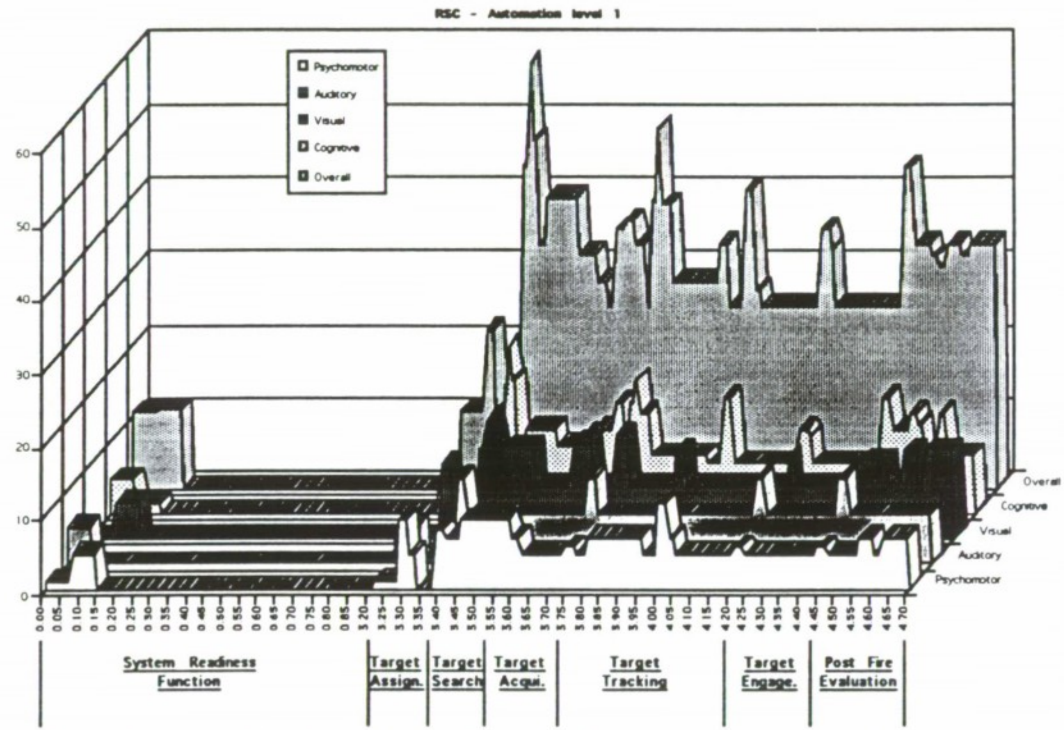

Figure 13.4. Channel workload levels for the RSC operator when a minimal function allocation trade-off is used. Excessive workload is reflected where workload exceeds 7 (bits) on an individual channel or 28 overall.

for the FOC operator (see Figure 13.5). At this increased level of automation, this operator's maximum workload falls below the 7-bit threshold. The RSC operator's high workload drops to about half of the original workload we observed (compare Figure 13.6 with Figure 13.2) and is less than that incurred in the first trade-off (Figure 13.4); but this operator still experiences excessive load in the last four system functions. These are the most critical functions the operator must perform. Consistent with previous results, the cognitive and visual channels are still heavily loaded.

We next looked at the minimum number of personnel required to operate the NSSMS. For this analysis, we examined the impact of allocating all remaining tasks to a single operator to determine if such a design would be feasible. Given the high load for the RSC operator in the second trade-off, we had no real expectation of favorable results when the FOC tasks were added to this position. Nevertheless, to uncover the problem areas for a potential single operator, we used the second reallocation scheme described above and reallocated all operator tasks to a single NSSMS operator, then ran the simulation. Some tasks involving coordination between operators (e.g., FOC to RSC communications) were eliminated since they were inappropriate to a single-operator system. This analysis was further bounded by an assumption of a single-radar, single-launcher configuration (some NSSMS configurations use two launchers and require two operators).

The preliminary WAA analysis indicates that combining both operators' functions into a single position does not dramatically increase the workload for a single operator (see Figure 13.7). In fact, the overall workload measure for the single NSSMS operator increases only slightly as compared with that of the RSC operator in a dual-operator configuration with the equivalent amount of automation. Consistent with all the RSC trade-off analyses, however, excessive workload at this level of automation remains in all functions from target tracking through the end of the mission.

CONCLUSIONS

Results from the task analyses, operator workload simulations, and reallocation trade-off studies we conducted consistently identified specific visual processing of system status information and cognitive decision-making tasks as high workload areas for both FOC and RSC operators.

The LOCAL control and ECM conditions, as predicted, imposed the most workload on operators. We determined that many of the high-workload tasks involved verification of normal system operations and could therefore easily be automated.

The transient spikes of high workload for the FOC operator indicate that this operator might be able to distribute over time some of the tasks associated with sudden spikes. This problem can be corrected with workload-reduction techniques for presenting information on the display. The RSC operator has the highest workload, as anticipated, even when increased automation is introduced into the operator performance models.

While the workload analysis provided an assessment of individual tasks that continue to impose high workload on NSSMS operators, specifically for the visual and cognitive channels, the task reallocation trade-off results provided a view of the impact of redistributing tasks on operator workload. These analyses reinforce the intuitive conclusion that increasing automation can reduce NSSMS workload. More importantly, they identify which specific tasks sustain loading and which processing channels bear the load. This is valuable information for guiding good human factors engineering of the display interface.

Our task-reallocation studies indicate the potential for consolidating operations into a single operator position, but not until more advanced automation is introduced into the system design. A solution to the immediate workload problem for NSSMS operators is to redistribute tasks more appropriately between both positions and to implement workload-reduction techniques for presenting information on the console displays.

ACKNOWLEDGMENTS

We would like to thank Clent Blaylock, John Dawson, Jr., and Tom Dryden for their expert knowledge about NSSMS operations. Special thanks is given to Herm Williams, Naval Research and Development, San Diego, CA, for his guidance in this research task.

REFERENCES

Army Research Institute. (1992). Manpower-based system evaluation aid (MAN-SEVAL) (Version 3.0) [DOS-based software application]. Aberdeen Proving Ground, MD: US Army Research Laboratory.

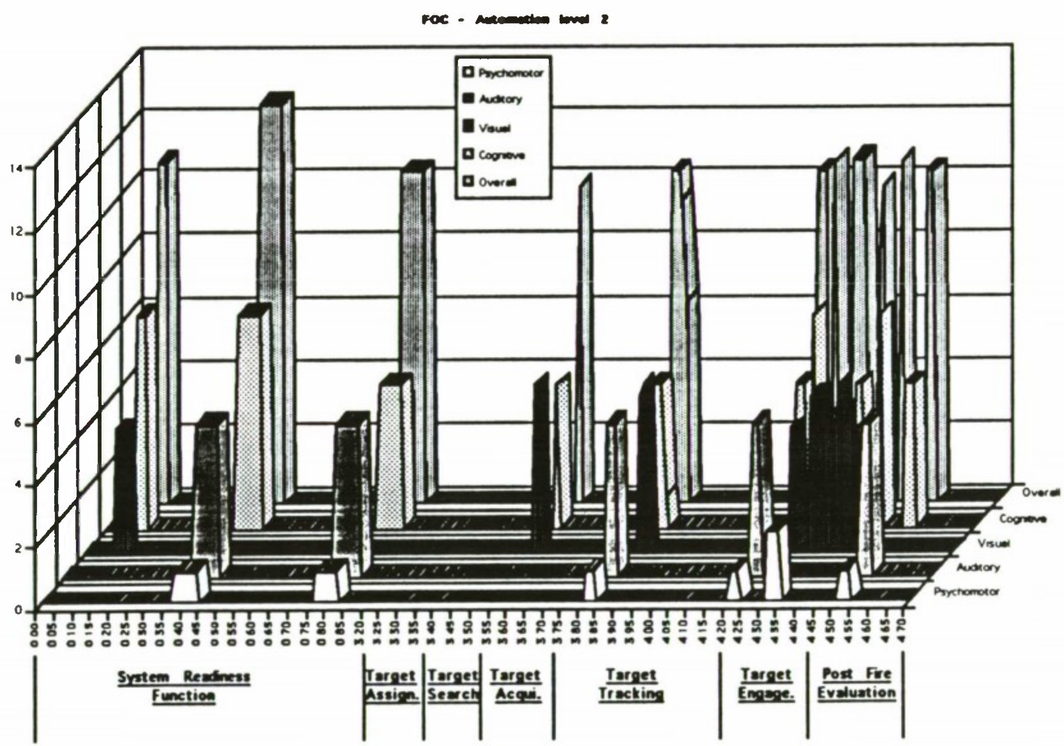

Figure 13.5. Channel workload levels for the FOC operator when a moderate automation trade-off analysis is used.

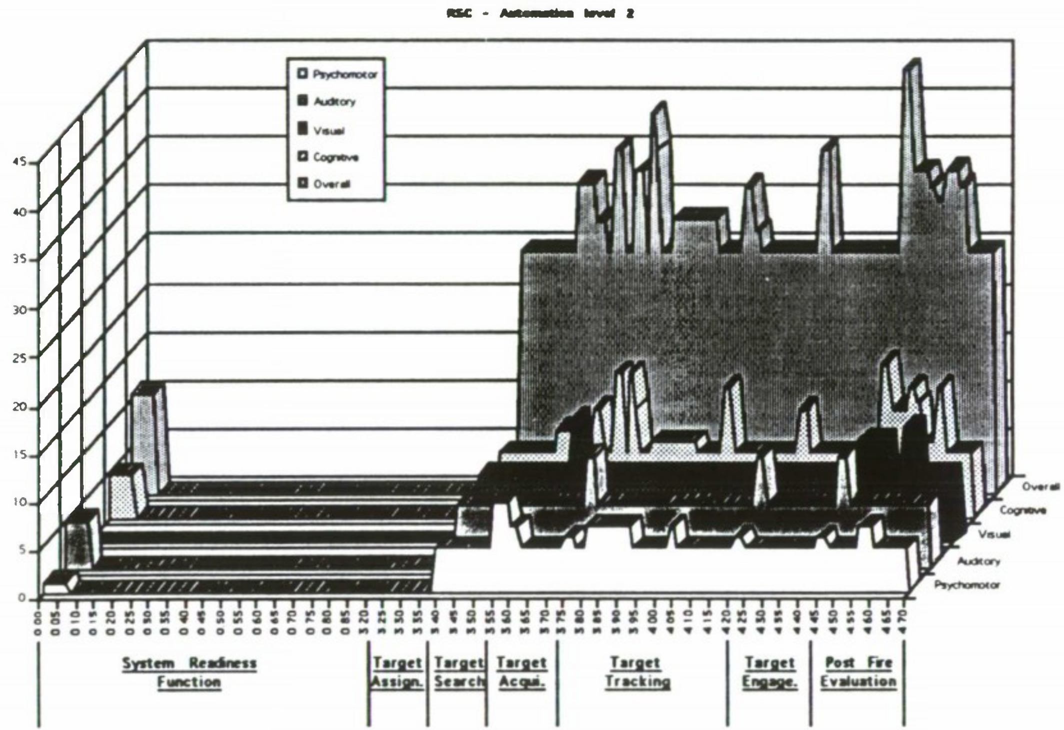

Figure 13.6. Channel workload levels for the RSC operator when a moderate automation trade-off analysis is used.

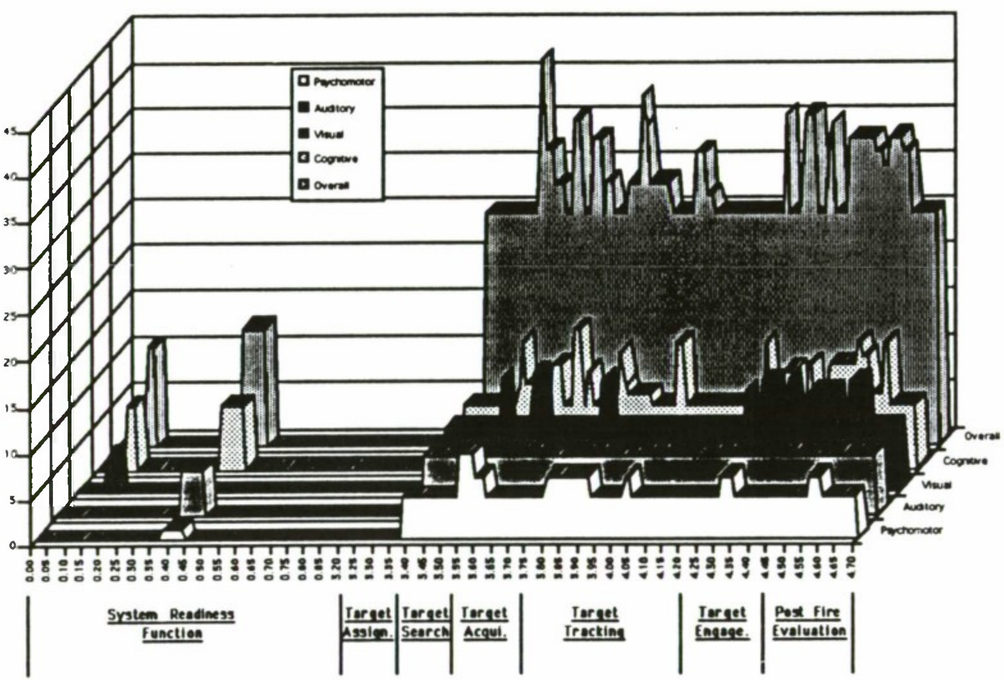

Figure 13.7. Channel workload levels for a single NATO Sea Sparrow Missile System (NSSMS) operator performing all NSSMS tasks when a moderate automation trade-off analysis is used.

Huey, B. M., & Wickens, C. D. (Eds.). (1993). *Workload transition: Implications for individual and team performance.* Washington, DC: National Academy Press.

Moray, N. (1986). Monitoring behavior and supervisory control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 2. Cognitive processes and performance* (Chap. 4). New York: Wiley.

Sheridan, T. B. (1988). Task allocation and supervisory control. In M. Helander (Ed.), *Handbook of human-computer interaction.* Amsterdam: Elsevier.

Swartz, M. L., & Wallace, D. (1994). Display design for real-time, high workload supervisory control systems. In *Proceedings of the First Conference on Automation Technology and Human Performance* (Vol. 2, pp. 235). Hillsdale, NJ: Lawrence Erlbaum.

Wickens, C. D. (1986). The effects of control dynamics on performance. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 2. Cognitive processes and performance* (Chap. 39). New York: Wiley.

14

FUNCTION ALLOCATION FOR THE DESIGN OF A RECONNAISSANCE VEHICLE[1]

D. F. Streets and R. J. Edwards

The twin drives of reductions in available human resources and technological advance have combined to produce proposals for vehicle design that use smaller crew complements. This design trend has also revealed the shortcomings in the techniques used for function allocation. One graphic demonstration can be found in the recent task-analysis studies of ground recon-naissance performed by Edwards and Streets (1994). In these studies, the requirement was to allocate residual functions among crew members, rather than between human and technology. This report documents the difficulties encountered in these tasks and the assumptions that had to be made, and discusses how observations made during data gathering enhance function allocation.

INTRODUCTION

The activity of function allocation is central to any predictive task analysis, yet it is supported by relatively imprecise techniques (e.g., Fitts' lists) that appear to be based upon intuition rather than science. A further problem—and one that is assuming increasing importance—is that current techniques do not address team interactions. With the current drive to reduce personnel levels in military systems, the problem of allocating residual tasks takes on a new significance.

New technology seeks to enhance system effectiveness by removing

certain tasks or subtasks from the human domain. Technology may, for example, increase data handling, storage, and transmission capability, but it cannot replace the human function of information interpretation. What technology is achieving is to increase the operator's available time by performing repetitive and time-consuming tasks, leaving the operator free to concentrate on more intuitive duties. The concept is that free time can be increased to the point where the residual duties of one crew member can be redistributed successfully among others, thus allowing a reduction in crew complement.

Available function allocation techniques fail to address the methods of achieving this redistribution. At best, an ad hoc approach may be employed; but this fails to address team dynamics or take account of the nature of the reallocated tasks. In this paper, we report on observations made during the collection of task-analysis data from an active reconnaissance unit that highlights an area function allocation techniques fail to address. We also demonstrate an iterative function allocation technique and discuss how our in-field observations are being applied, at a relatively low level, to improve human-human function allocation.

BACKGROUND

The principal function of armored medium reconnaissance is to provide timely and accurate combat information to higher formations. In the British Army, the base vehicle for this activity is the Combat Vehicle Reconnaissance (Tracked), or CVR(T), which has three crew members—a commander and gunner located in the turret, and a driver located in the hull. Compared with the rest of the British Army armored fleet, this is a relatively old vehicle, and the desire is to replace the CVR(T) with a significantly enhanced vehicle, the Tactical Recon-naissance Armoured Combat Equipment Requirement (TRACER).

The design of TRACER is expected to take full advantage of recent advances in integrated vehicle electronics architecture (vetronics) and military equipment technology. The philosophy behind vetronics is very similar to that governing avionics in high-performance aircraft. A central processor connects each system and subsystem through a data bus architecture. This arrangement allows system integration and enhanced information flow and exchange. It is this potential increase in information-processing efficiency that offers the scope for reductions in crew workload and, possibly, crew numbers, and has led to the sugges-

tion that TRACER could possibly have a crew complement of two.

The Defence Research Agency Centre for Human Sciences was charged with performing a series of task-analysis activities to support studies for TRACER. These activities have been reported elsewhere (Edwards & Streets, 1994). In outline, the first series of studies were aimed at documenting current reconnaissance practices, while the second series were predictive studies that specifically addressed surveillance activities based on the best available information on scenarios for future deployment. The information presented in the second series would be used as a design tool for the crew workstations within the vehicle. It was also anticipated that the analysis would indicate areas of crew work overload.

CURRENT RECONNAISSANCE

The overall crew tasks of a CVR(T) are oriented toward fulfilling the primary aim of reconnaissance. Within the crew, each human has a set of well-defined core roles. The main task of the driver, for example, is to move the vehicle tactically using the fastest and safest route and without causing the other crew members undue distress. In performing a given mission, however, crew cooperation is paramount; for example, the driver may also be expected to provide route information, such as ground conditions, state of bridges, or possible ambush points. The operation of the vehicle depends upon close cooperation among the crew and, in particular, the commander and gunner. The nature of this cooperation is determined by the scenario and by a set of rigidly demarcated procedural rules.

Allocation of current functions among the crew members was recorded by structured interview of serving crews, discussions with subject-matter experts, and participation in training exercises (Edwards, 1992). These methods produced the type of information shown in Table 14.1.

The uppercase *X*'s refer to a crew member's core task, while the lowercase *X*'s indicate a secondary task in which that crew member might cooperate with another or in which systems tasks are performed. This relatively simplistic presentation of self-selected function allocation provided the baseline data for subsequent studies and also revealed some of the dynamics of duty allocation within a group.

Table 14.1. Function alloeation among the three-person erew in a combat reconnaissance vehiele [CVR(T)]

TASK	COMMANDER	GUNNER	DRIVER
Surveillanee	X	x	x
Radio watch	X	x	x
Navigate	X	x	
Drive			X
Direct driver	X	x	
Maintenanee	x	X	X
Stowage	x	X	X
Start up drills	X	X	X
Cook	x	X	X
Encode/decode	X	x	
Range eards	X	x	x
Load gun	X		
Fire gun	x	X	

During the eolleetion of these data, it beeame apparent that task alloeation and individual workload in a three-person crew are driven by rank and experience. When the vehiele is in motion, the commander will perform all the key funetions, sueh as eommunications and surveillanee. The gunner's role is to aid the eommander; it is rare for the gunner to perform any eommand funetion unaided. It was noted on many oecasions that the eommander used the map to mark the route taken and to reeord information flow. It was rare that other crew members saw or used the map. Indeed, the only tasks that were generally not performed by the eommander were driving and gunning.

It is these characteristics that make function alloeation in a reconnaissance vehicle so difficult. Models of teamwork (e.g., METACREW, in Plocher, 1989) work to a set of command rules that address how indi-

viduals manage work. Task sharing and switching is not addressed, nor are any procedural rules.

When the vehicle is stationary, the roles of surveillance and communication are shared among the crew. This is known as the "stag" system. In this case, each crew member will take equal turns at each system task, but the commander will have overall control and responsibility. This very tight control ensures that the system operates in an efficient and effective manner, and it is the basis of the military training system for reconnaissance troops.

The rigidity of this system may be gauged from a recent trial in which reconnaissance crew members were presented with two identical operational crewstations that could be used for either command or driving functions. The concept was that tasks could be switched between members in response to changes in the mission scenario. What was observed was that crew functions were self-distributed by rank, so that, even when the more senior soldier was performing the driving function by choice, he also performed the traditional command functions; the second crew member merely provided support. Although this may be viewed as a consequence of the military training system, it does highlight a significant problem, namely, that current function allocation techniques cannot take into account rank and experience hierarchy. It is well documented that rank and hierarchy are powerful determinants of how systems actually operate. A proper understanding of these dynamics is essential. The consequences of being unable to account for rank and hierarchy in function allocation is illustrated in the next section.

PREDICTIVE TASK ANALYSIS

The second series of task-analysis studies was aimed at characterizing the activities associated with surveillance and engagement tasks in a TRACER concept vehicle. A full account may be found in Edwards and Streets (1994).

It was assumed that the crew would be designated as a commander and a co-commander, with the gunner's duties being shared between vetronics and the two remaining crew members. A further assumption was that all tasks would be interchangeable depending upon the nature of the scenario. Appropriate scenarios and outline equipment performance parameters were made available.

As noted above, the gunner's on-vehicle duties are directed at supporting the commander, which leaves few primary tasks to be performed totally by vetronics. The outcome is that functions are allocated primarily between the remaining crew members' primary duties. To perform this allocation, a set of task-synthesis rules that characterized the remaining crew members' primary duties had to be produced. After a working taxonomy was established, a set of task-synthesis rules was derived. These were:

(i) Crew are referred to as commander and co-commander. The commander has sole control of communications flow into and out of the vehicle; the co-commander has sole control of the driving function. These primary crew functions can be transferred between crew members only when the main armament is manned and ready for use.

(ii) Driving is an autonomous activity and the co-commander has sole control over the route and speed at which the vehicle travels. When driving, the co-commander makes no primary contribution to any other surveillance duties except route reconnaissance and survey.

(iii) Unless otherwise stated, the co-commander has sole responsibility for off-vehicle duties.

(iv) The activities of driving or communications cannot be combined with engagement.

(v) The activities of weapon and engagement or weapon management and driving cannot be combined. Weapon management is defined as keeping the main weapon in readiness when the vehicle is moving.

(vi) The crew member who makes first visual contact with an enemy objective completes the engagement sequence.

These rules were based on the behavioral premise that no more than two dissimilar manual tasks could be performed simultaneously. Cognitive workload could not be taken into account because the performance parameters of the surveillance devices and possible data-handling capabilities of the vetronics were ill-defined. Clearly, it is impossible both to read text and to examine a picture for discrete changes; however, it is not known if information exists on the ability to observe a scene both for driving and for surveillance purposes, and if there would be any performance decrement.

Table 14.2. Core duties for each crew member in a CVR(T)

COMMANDER	CO-COMMANDER
Surveillance	Drive
Communications	Route reconnaissance
Survey	Troop security
Navigation	Survey
Troop security	
Weapon management	
Troop control	

Table 14.2 shows the core duties defined for each crew member from these task-synthesis rules. The information gained from our earlier studies was used to enhance this allocation, but the possible effects of rank and experience were purposely ignored. Because the task-analysis exercise was concerned with surveillance duties, system tasks such as stowage and maintenance were not considered. It was unnecessary to undertake function allocation between humans and surveillance devices because such systems enhance human performance—they cannot replace the human. Table 14.3 shows an attempt to allocate other equipment, by function, to the crew. Performance parameters were poor, and allocation was based on the task-synthesis rules set out above. "Primary User" is defined as the crew member who is expected to be the priority user of that system under all conditions.

The formal task-analysis techniques used were a combination of function flow diagrams and operational sequence diagrams. Function flow diagrams were chosen because they permitted the representation of information flow and could be altered to show each crew member's activity. The basic outline for each function flow diagram was a preparation phase, a number of activities that had to be completed to fulfil the task, and an either/or statement. This allowed the task to be continually recycled, to be halted, or to progress on to a related activity. Each function flow diagram was divided into three parallel flow lines. The central flow line described the functionality of the system task. System tasks were

Table 14.3. Allocation of equipment, by function, to crew members in a CVR(CT)

EQUIPMENT	PRIMARY USER	SECONDARY USER
Audio and digital communications	Commander	Co-commander
Battlefield Management System (BMS) - Moving	Commander	Co-commander
BMS - Stationary	Equal priority	
Land Navigation System (LNG) - for driving	Co-commander	Commander
LNG - for information	Commander	Co-Commander
Electronic Map System (EMS)	Commander	Co-Commander

given individual reference numbers to allow a degree of ordering. To the left and right, respectively, of the system flow line were the commander and co-commander flow lines. Text to either side of a system task box indicated the duties each performed in accomplishing each activity. Concurrent tasks were also indicated by text between each system task box. Information flow to and from the system, and from outside the system (i.e., squadron, or section headquarters, SHQ) to each crew member could be represented by directional arrows.

A total of fifteen functional flow diagrams supporting identified surveillance tasks were derived. An example is shown in Figure 14.1. This approach allowed visualization of the tasks each crew member would need to perform and permitted function allocation by default. The principle employed was that a task could only be performed if a crew member was available.

The output of the function flow diagram served as the database for the formal task analysis. A review of task-analysis methods suggested that the most appropriate technique would be the operational sequence diagram, since it can represent the flow of information (Beevis, 1992) and show individual activities of teams of workers performing tasks

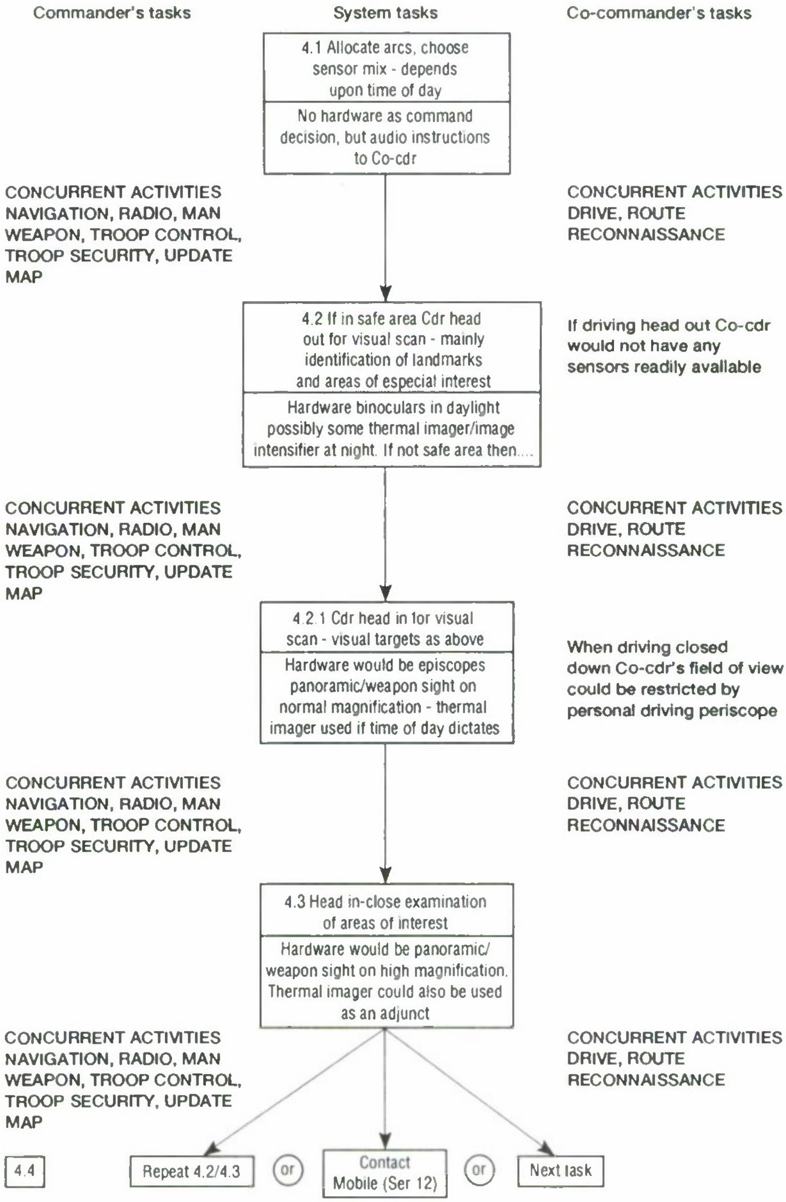

Figure 14.1. Function flow diagram for observation (mobile).

(Laughery & Laughery, 1987). Time-line analysis was rejected because of its imprecision; flow process charts and hierarchical methods were rejected because of their relative complexity, particularly for the representation of multiple and concurrent tasks.

The function flow diagrams represent the performance of single tasks; interactions are shown but not explored. The operational sequence diagrams were able to visualize these interrelationships and identify areas of task overload. More significantly, they were able to show the extent to which tasks would need to be shared or switched to allow two crew members to operate the system. An example is shown in Figure 14.2.

The scenario supporting this operational sequence diagram is for a static observation made by a single vehicle. Support is denied, so the vehicle is required to carry out an engagement sequence unaided. The task-synthesis rules (above) have been used as the basis for determining how tasks are shared and switched. The two prime determinants are rules iii to vi, which set out primary roles and forbidden task combinations. As Figure 14.2 shows, once the co-commander has prepared the vehicle to move and has remounted, there is a staged hand-over of system tasks until the commander's sole duty is control of the weapon system. At the end of the engagement sequence, there is a staged return of duties.

Although this allocation appears, superficially, to be plausible, there are a number of serious faults. At the commencement of the engagement sequence, the co-commander may be expected to perform up to ten tasks or subtasks, while the commander has a single duty to undertake but has no direct communication with higher formations. It is hard to imagine that a commander would willingly hand over duties in the manner described, but the absence of a function allocation technique that takes account of rank and experience could lead to this conclusion. Assumptions made from this example could be erroneous and could be translated into poor equipment design.

We have reexamined this operational sequence diagram, and the task-synthesis rules, in the light of our observations on rank and experience as significant factors in determining function allocation and have arrived at revised conclusions. It is clear that a further task-synthesis rule needs to be drawn up; our tentative new working rule at present is:

(vii) Rank and experience dictate that the commander maintain control of communications to and from the vehicle at all times when the vehicle is in motion. When the vehicle is stationary, control may be shared between the crew.

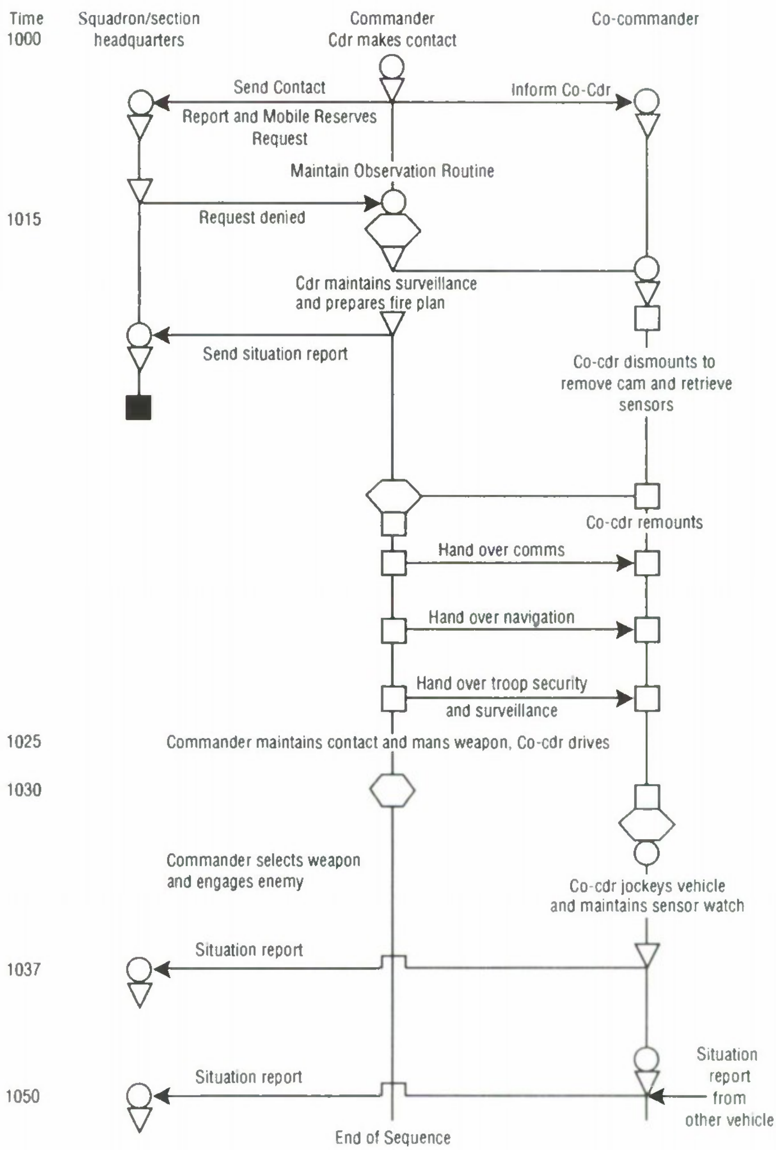

Figure 14.2. Operational sequence diagram for task switching.

Rule iv is rewritten as:

(iv) The activity of driving cannot be combined with engagement.

The outcome of these rules is that the commander, by retaining the communications task, may maintain control of the vehicle throughout the engagement sequence, with a consequent reduction in the workload of the co-commander. The problem with this iterative approach to function allocation is that a suitable test of validity does not yet exist. Unlike aviation or industrial scenarios where missions are of finite length and have clearly defined goals, in military land-based systems these conditions are not normally fulfilled. Under such circumstances, it is possible that traditional function allocation techniques are inappropriate and that a combination of intimate knowledge of current activities and the dynamics controlling crew performance, coupled with an iterative approach, is the only valid technique. It is equally possible that the approach described for land-based reconnaissance is valid only for this system.

CONCLUSIONS

This paper has described some of the problems encountered in attempting to perform function allocation between human and human, rather than human and machine, in a ground-based system. At a time when the drive appears to be to reduce crew levels, it is essential that new techniques for human-human function allocation be derived. A major factor in determining function allocation in a three-person reconnaissance crew is rank and experience. This factor assumes even greater significance when the attempt is to allocate functions to a two-person crew. Whether this would be such a strong determinant if human-human function allocation were being performed on a reduced crew complement for larger systems (e.g., self-propelled guns) remains to be determined. From the evidence outlined in this paper, it is suggested that the first steps in deriving techniques must be to clearly define the system and to identify the high-driver functions and the acceptable departures from hierarchical command structures.

REFERENCES

Beevis, D. (Ed.). (1992). Analysis techniques for man-machine systems design (NATO Technical Report AC/243 [Panel 8] TR/7, Vols. 1 & 2). Brussels: NATO Defence Research Group.

Edwards, R. J. (1992). *Report on Exercise Lively Lancer—16/5th Queens Royal Lancers Regimental Exercise 10 - 13 April 1992* (Army Personnel Research Establishment Working Paper 22/92). Farnborough, UK: Army Personnel Research Laboratory.

Edwards, R. J., & Streets, D. F. (1994). Task analysis studies of ground based reconnaissance. In *Proceedings of the 35th DRG Seminar on Improving Military Performance Through Ergonomics* (pp. 102-128). Brussels: NATO Defence Research Group.

Laughery, K. R., & Laughery, K. R., Jr. (1987). Analytical techniques for function analysis. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 329-354). New York: Wiley.

Plocher, T. (1989). METACREW: Simulating operator teams in a sensor data processing system. In G. R. McMillan, D. Beevis, E. Salas, M. H. Strub, R. Sutton, & L. van Breda (Eds.), *Applications of human performance models to system design* (Defense Research Series, Vol. 2, pp. 313-323). New York: Plenum.

15

FUNCTION ALLOCATION FOR REMOTELY CONTROLLED MINESWEEPERS

L. C. Boer

Function analysis and function allocation are described for a new minesweeping system based on remote control of "drones." The critical question for system design was whether one operator on board a mother ship could manage four drones at once, using remote control. The results of a human-in-the-loop simulation revealed which conditions of automated support produce acceptable performance of the human-machine system. A general conclusion of the simulation study is that one of the allocation criteria should be to utilize the human mental capacity available, even when the system requires only a fraction of this capacity.

INTRODUCTION

In a study for the Royal Netherlands Navy, function allocation was performed together with a function analysis to define the functions required by a minesweeper system to fulfil the system's mission. The focus of analysis was the role of the human operator. Those functions that involved a human operator were analyzed in more detail; functions not involving humans were not analyzed further. Function allocation and function analysis were thus coupled interactively, as shown in Figure 15.1.

The function analysis was hierarchical. At the top level, the complcte system was addressed. The system, consisting of four "drone" minesweepers remotely controlled from a mother ship, needed to perform two basic functions: minesweeping and navigation. A preliminary

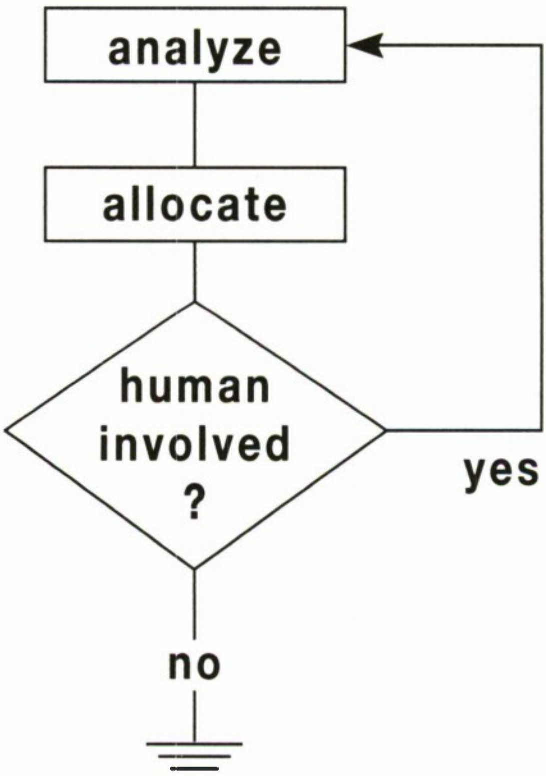

Figure 15.1. Interaction between allocation and analysis of function.

consideration of function allocation revealed that the "minesweeping" function requires no human involvement except for a minor degree of supervision and authorization of the start and end of the sweeping operation. This function was not analyzed further. Human involvement was foreseen in the "navigating" function. In a further analysis, a distinction was made between the subfunction "planning," which provided a plan for how to sweep a designated area, and the subfunction "drone control," responsible for executing the plan. Both functions require human involvement. The concept of remote control is new for the Royal Netherlands Navy. Thus, the subfunction "drone control" required special attention, as shown in Figure 15.2. Remote control is an attractive design option, first, because it increases the safety of minesweeping and, second, because it promotes reduction in forces, which is a long-term policy in many NATO countries.

"Tracking" is a subfunction concerned with keeping the drones on their designated track. "Speed control" is a subfunction concerned with maintaining the designated speed. "Platform" is concerned with the integrity of the drones and their technical systems. "Traffic" is concerned with watching out for other vessels and evading if necessary.

The "platform" and "traffic" subfunctions take into account particular aspects of the environment. Damage to the drones' platforms is not unlikely considering the possibility of mines' exploding in the vicinity of the drones. Other traffic is not unlikely because the system will be designed both for wartime and peacetime operation. In peacetime, other traffic cannot be denied access to the area to be swept. Operator involvement was deemed necessary because the "platform" and "traffic" subfunctions require flexibility and improvisation—functions at which humans still surpass machines.

A simulation of the drone-control function was set up in order to see whether one operator could control four drones at once, managing the four subfunctions outlined above. In other words, the operator was involved not only in extraordinary situations (platform damage or dangerous traffic), but in continuous tracking as well. One reason to consider a more extensive allocation to the human operator is financial cost. Instead of automating as much as possible, the approach advocated here is to allocate more functions to the human operator if the operator's mental capacity allows for additional activities. This saves automation costs. Moreover, a more satisfying job is created, promoting human well-being (Drury, 1994; see also Fitts, 1962). Thus, careful allocation

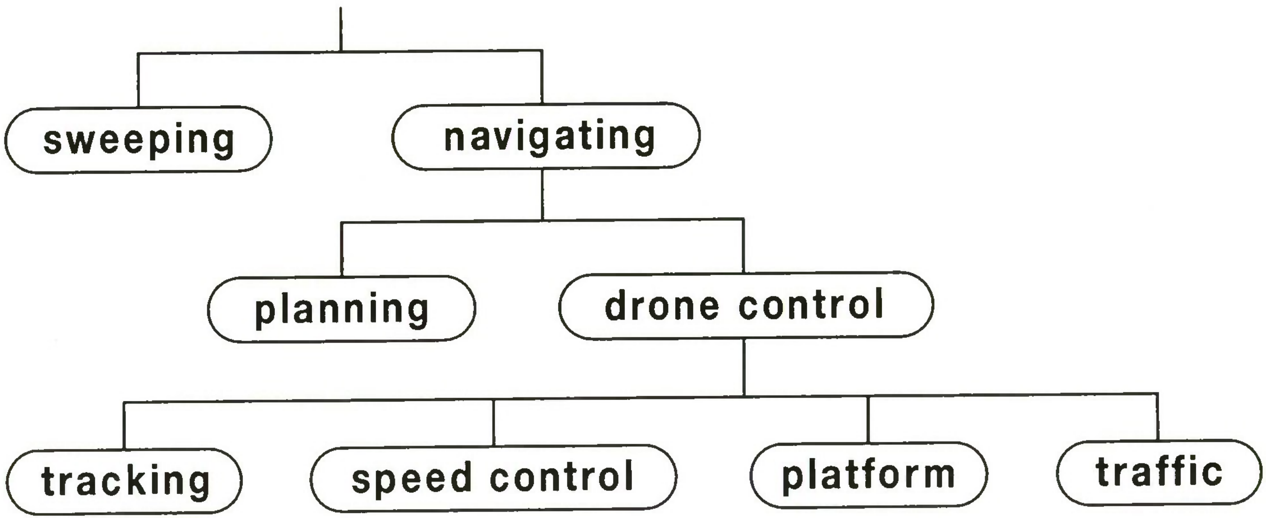

Figure 15.2. Three levels of function analysis for a minesweeper system. The human operator in the subfunction "drone control" is the focus of the current paper.

of function not only can save money but also can reduce operator frustration and boredom as well, making the job more challenging.

Two types of simulation can be used to assess system performance and operator workload: fast-time simulation and human-in-the-loop simulation. In fast-time simulation, a computer model of the human operator is part of the simulation. Typical parameters include the time to complete an action, the probability of success, and the mental load on the operator. By running a fast-time simulation many times, indications of average performance of human-machine systems can be obtained. Fast-time simulations are promising tools, but somewhat risky to use at the current state of knowledge about human factors. The problem is that the human factors discipline has no complete model for operator performance, but fast-time simulation requires such a model. As a consequence, unsound and questionable assumptions may abound in fast-time simulation. There are also some reasonable assumptions; for example, for simple tasks where time to completion conveys all the information required, or for tasks known in great detail, such as cockpit tasks, where the time to operate each individual switch, the probability of error, and the mental load factor are known. The assumptions are weak and debatable, however, when applied to complex tasks and multitask situations. The consequence is pseudoaccuracy. The simulation model produces accurate time lines of mental workload, but their validity is questionable. Attempts at fast-time simulation based on information-processing models of human performance such as the Goals, Operators, Methods, Selections (GOMS) model (Card, Moran, & Newell, 1986) are under way, but it is not yet clear whether this is a viable alternative.

Human-in-the-loop simulation uses a computer model of the system together with a real human operator. The flight simulator is the classical example: a real pilot operates a simulated airplane. Human-in-the-loop simulation requires a "real" interface between human and machine; the development of an interface was part of the project. (Fast-time simulations do not require human-machine interfaces.) The advantage of human-in-the-loop simulation is the presence of real humans with real mental capacity, which frees us from the assumptions associated with fast-time simulation.

For these reasons, the present study used a human-in-the-loop simulation. In the simulation, both system performance and operator workload

were measured. Performance criteria for operational acceptability were formulated in advance.

SIMULATION

Apparatus. There were two displays, one for tracking, the other for the remaining tasks. A special control panel was used for tracking, and a mouse and the computer keyboard were used for the other tasks. Figure 15.3 shows the setup.

Subjects. Eleven young adults participated as paid subjects. On day 1, they were trained on the tasks; on day 2, they performed the tasks for data collection.

Tasks. The tasks allocated to the subject were: (a) tracking, (b) platform, and (c) watching. Speed control was automated; the drones sailed at a constant speed. The tracking task was presented with various degrees of automated support. Control by rudder was the lowest level of automated support; control by a course autopilot was the medium level; and course-autopilot control plus presence of a path predictor was the level just below full automation. A high-quality "radar view" on the first display showed the position of the designated track relative to the individual drone. Figure 15.4 gives an idea of this human-machine interface. For the highest automation level, a line protruding from the drone showed the path prediction for the coming 20 seconds. The dependent variable was the deviation between the actual path and the designated track.

The sweeping plan contained a number of straight tracks. The scenario specified wind (constant) and current (different for different parts of the area). Both wind and current were at, or close to, the limits considered just acceptable by the Royal Netherlands Navy.

The platform and watching tasks used the second display. They were represented with some abstraction because the details of these tasks were not known at the time of the experiment. The platform task was to react to "alarms" presented every 4 minutes. An acoustic alarm annunciated the alarm. At the same moment, one of the three windows in the upper part of the display was illuminated. The subject had to extinguish the window by clicking it with the mouse. Then, one of the other windows was illuminated and had to be clicked. Finally, a third window was illuminated and had to be clicked. After these three actions, a two-number addition was presented. The subject had to enter the solution

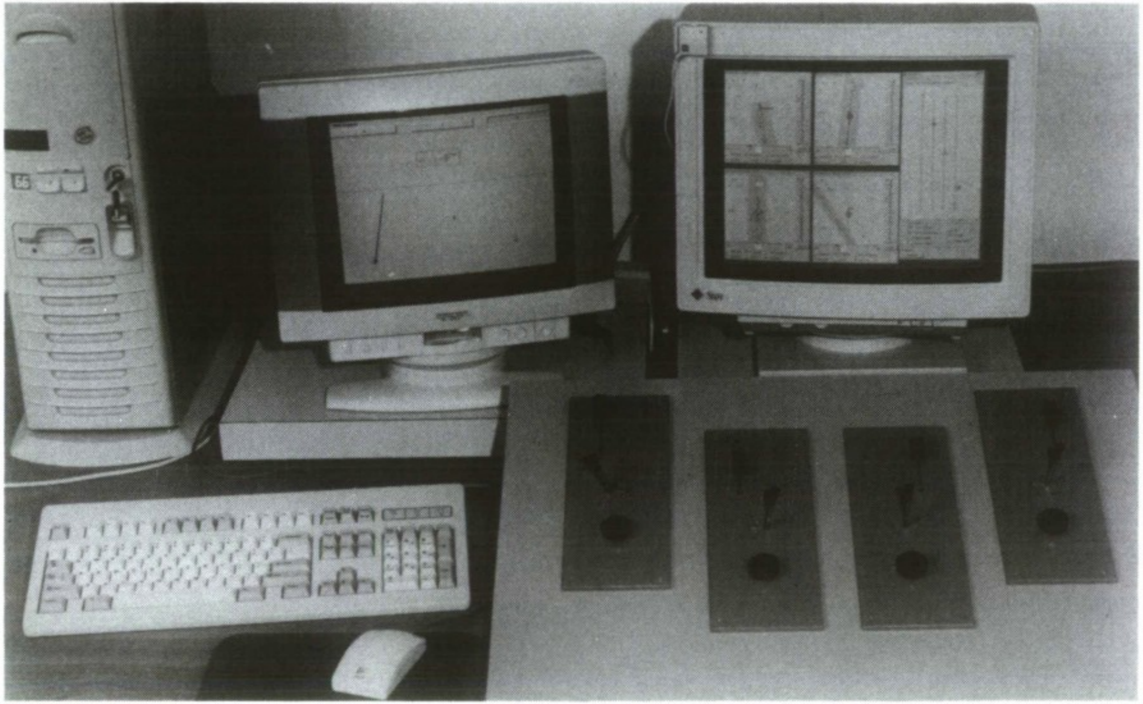

Figure 15.3. The simulation setup. Displays are for platform and watching (left) and tracking (right; see Figure 15.4 for more detail).

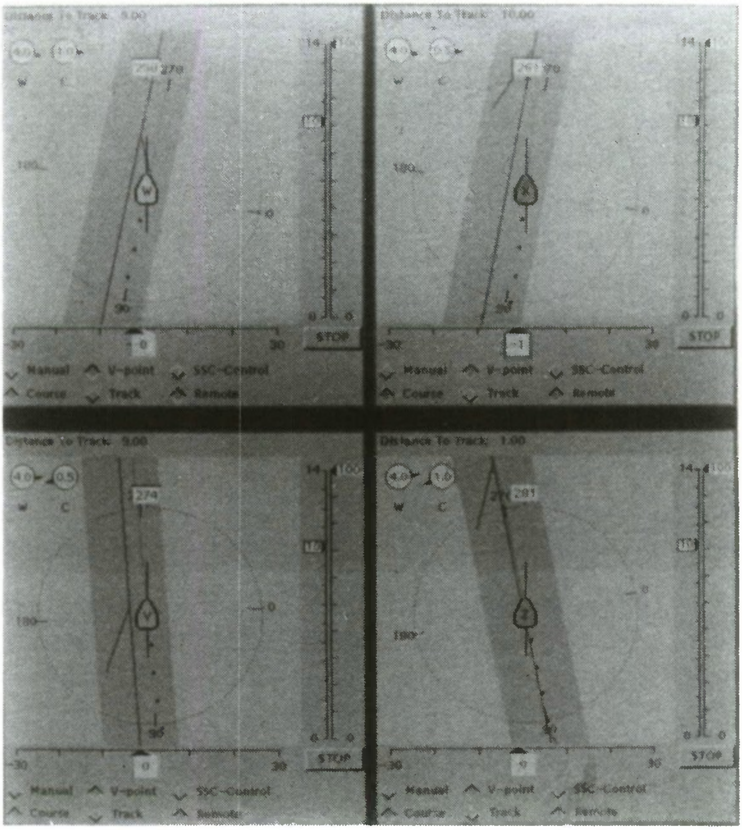

Figure 15.4. The radar view for the tracking task.

using the keypad of the computer. The dependent variables were the number of correct solutions and the time between the alarm and the "Enter" command.

The watching task was to monitor arrows appearing every 20 seconds in the lower half of the second display. Subjects had to react by pressing the space bar if an arrow pointed anywhere between east and south. The dependent variable was the number of missed target arrows.

The instruction was to sail the drones over their designated track, to react to platform alarms, and to watch for target arrows. There were six

conditions defined by the three levels of tracking automation and the number of drones under control (two or four). The platform and the watching task were the same across the six conditions. Each condition lasted 30 minutes. The order in which the conditions were presented was randomized across subjects.

Mental workload was measured subjectively. Immediately after a condition, the subjects were asked to report their mental effort as a number between 1 (no workload) and 5 (very high workload). These univariate ratings are at least as sensitive as multivariate ratings (Hendy, Hamilton & Landry, 1993). Moreover, univariate ratings are easier to collect and to process.

RESULTS

Tracking. Figure 15.5 shows the interval around the designated track within which the drones sailed 95 percent of the time. The figure also shows the standards of operational acceptability. The level of automation is indicated along the x-axis. At the extremes, the results are very

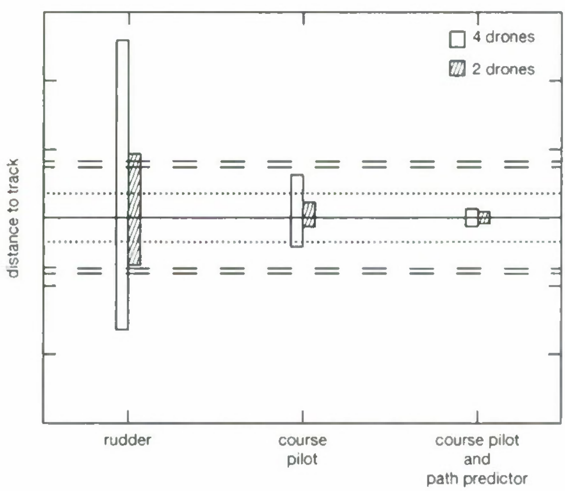

Figure 15.5. Tracking performance as a function of automation level with control of two drones or four drones. (The dashed lines show the boundaries of operational acceptability.)

clear: tracking performance was unacceptable for the lowest level of automation, rudder control; tracking performance was acceptable for the highest level of automation, course-autopilot control aided by path prediction. These results held regardless of whether the subject controlled two or four drones (although tracking performance was better when controlling two drones). At the middle level of automation, control by a course autopilot, acceptability of performance depended on the standard applied and the number of drones under control.

Platform and watching. Figure 15.6 shows performance on the platform and watching tasks as a function of tracking condition. In either task, performance reflected the difficulty of the tracking task; that is, performance on both the platform and the watching task improved when more tracking automation was provided or when the number of drones was reduced from four to two. For both tasks, performance was acceptable except in the most difficult tracking condition (controlling four drones by rudder). For all other conditions, the reaction times to platform alarms and the number of missed target arrows were acceptable. Strict standards, however, were available for the watching task only.

Mental workload. Figure 15.7 shows the average level of mental workload reported by the subjects. Mental workload decreased if the level of automation was increased or if the number of drones was reduced from four to two. Mental workload was close to the maximum for the most difficult condition; mental workload never exceeded a level of "slightly above medium" for the other conditions.

DISCUSSION

The conclusion of the study is that one operator can do more for the system than just providing intervention in extraordinary situations, such as platform damage or collision avoidance. The operators were able to monitor the drones' platforms adequately and to watch out for other traffic; moreover, the operators had sufficient spare capacity to control four drones at once using a course autopilot. The fact that their tracking performance was not always acceptable is probably irrelevant considering that real operators will have more experience and, hence, will meet all operational criteria.

The operators rated the combined level of mental workload when performing these tasks simultaneously as "slightly above medium." When

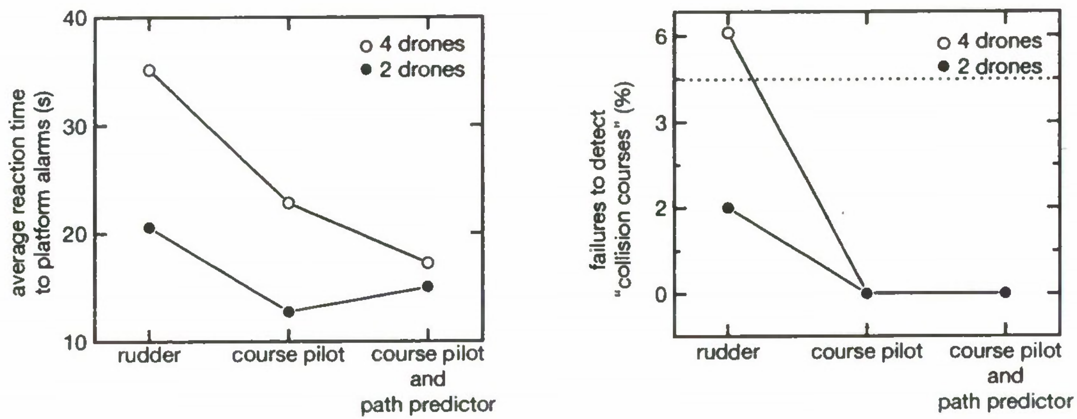

Figure 15.6. Performance on the platform and the watching tasks as a function of the automation of the tracking task with control of two drones or four drones. (The dashed line shows the boundaries of operational acceptability for the watching task.)

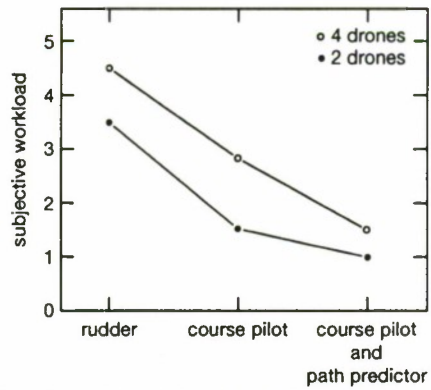

Figure 15.7. Mental workload for the various conditions of the drone-control task.

a path predictor was available, tracking performance was excellent and the operators estimated their workload as low, perhaps too low.

Operator capacity comes in units, not in fractions. At initial allocation, the system may need the fraction, but still gets the unit. The position advocated in the present paper is to use the available operator capacity in the best possible way. It would be unwise to load human operators to the limits of their mental capacity, because this deprives the system of safety margins. It would be equally unwise, however, to *under*use the human operators. Mental capacity is a valuable system resource. Using this resource a little more does not increase the personnel requirements, can save costly automation, and can provide the operator with a more satisfying job.

REFERENCES

Card, S. K., Moran, T. P., & Newell, A. (1986). The model human processor. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and performance: Vol. 2. Cognitive processes and performance* (Chap. 45). New York: Wiley.

Drury, C. G. (1994). Function allocation in manufacturing. In S. A. Robertson (Ed.), *Contemporary ergonomics: Proceedings of the Er-*

gonomics Society's 1994 Annual Conference (pp. 2-16). London: Taylor and Francis.

Fitts, P. M. (1962, January). Functions of man in complex systems. *Aerospace Engineering, 21*, 34-39.

Hendy, K. C., Hamilton, K. M., & Landry, L. N. (1993). Measuring subjective workload: When is one scale better than many? *Human Factors, 35*, 579-601.

16

FUNCTION ALLOCATION IN ARMY SYSTEMS[1]

J.-P. Papin and J.-Y. Ruisseau

During the design of a modern system, the crucial problem arises of knowing who (which member of the crew or which automaton) does what (function to be fulfilled). Today, decisions on function allocation can be made using a scientific approach. The Human Factors Center of the French Army is trying currently to put in place a standard approach. This approach is based on an analysis of the requirement, followed by an analysis of functions independent (as much as possible) of specific technical solutions. The process is completed by analyzing the work of crews in operational systems similar to the planned system. From there, it is possible to perform computer modelling of a typical scenario in which the elementary activities that must be brought into play in the system are represented. Different combinations of these activities are arranged to be performed by an operator (human or automatic) in order to find an optimal solution for the allocation of functions. Although simple in theory, this approach is actually complex to put into practice because the human activities that must be performed to fulfil a given task depend very much on the interface chosen and thus on a particular technical solution. That is why the approach of optimizing the system must be continued during the product development phase. This can be done by validation using functional computer-based mock-ups. The methods employed are: the analysis of tasks for systems similar to the future system (e.g., helicopters); the analysis of requirements; the analysis of functions during development, taking into account technical solutions that are imposed (e.g., reconnaissance

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[1]Translated from the French by D. Beevis.

vehicle, command post vehicle); computer modelling of the scenario (e.g., tank, reconnaissance vehicle, helicopters); computer modelling of the workstation (e.g., command post vehicle, gunner); future dynamic software modelling; and direction of manikins by software such as MicroSAINT.

INTRODUCTION

The design of modern weapon systems poses the problem of the division of roles among humans and machine: who (operator, automaton, crew) does what (fulfils a function, for example). Today, a scientific approach can be used to make decisions on the allocation of the diverse functions at the heart of a system. This approach must be integrated with the general approach to design in a systematic fashion, to produce solutions based as much on system architecture as on allocation of function.

The Human Factors Center of the French Army currently works in this way and has put in place a standardized approach based on an analysis of needs involving a functional analysis independent of probable technical solutions or possibilities. An analysis of tasks based on a system similar to the planned system permits the possibilities for the future system to be envisaged. These possibilities can be understood in terms of elementary activities, representing the likely future activities, and modelled in the form of various types of scenario that reflect the operational requirement.

Various computer tools currently permit at least partial responses to the problems thus raised, and allow solutions to be proposed to the designers that respond as well as possible to overall constraints—issues that are as much operational as technical.

ANALYSIS OF THE REQUIREMENT

The first step in the design of a new system is an analysis of the requirement. This is a familiar practice for the ergonomist because analysis of requirements is a fundamental principle of an ergonomics intervention, with known scope and extent; however, analysis of requirements is sometimes much less in evidence in the world of engi-

neers and operators. It falls to the lot of the human factors specialist to highlight the importance of this step in the case of the human. In effect, the human is today, and will remain for a long time, a major determining element in the development of a weapon system.

An example of this approach can be seen in the case of the modular armored vehicle (VBM) project. The goal of this project is to procure for the Army a family of vehicles suited to a range of operational needs: infantry troop transport, command post, weapons carriage, direct fire vehicle, etc. In the case of the VBM, an initial analysis of the requirement was based on an analysis of the current limitations of vehicles that meet these operational needs only partially, and on an analysis of evolutions in design concepts that are likely in the medium term. From that analysis, we extracted the principal factors before orienting our thinking. Thus, it appeared that, in a personnel carrier version (VTT), it was difficult to consider separating the two functions of the vehicle commander: to command the vehicle and to command the embarked combat group. This had a marked influence on the design of the future vehicle.

FUNCTION ANALYSIS

An analysis of the requirement brings out the principal constraints that affect the system and its overall performance. Function analysis makes it possible to determine the principal functions the system must provide, how to provide them, and under what environmental conditions they can be assured. It also allows at least an initial attempt at defining the allocation of the various functions between human and machine. At this level, it is a case of knowing what has to be done and how it has to be done to ensure the optimal effectiveness of the system.

An example of such an analysis is provided again by the VBM project. The principal missions that could be committed to each element of the VBM family were defined, analyzed, and validated at the operational level. Each function necessary for the accomplishment of a mission was identified, and the constraints characterizing each function were examined. This process was carried out for all the requirements specified for the family of vehicles, which permitted a precise determination of the directions to be followed in defining the design more closely. Among other things, the choice of certain technical solutions followed directly from this analysis, whether it was for the purely system portions

(functions, mobility, fire, protection) or the portion better labelled "human" (ergonomics, human factors, etc.). An example of such a choice is the determination of the rear-opening doors in the personnel carrier version. There were two opposing concepts for this design element: the technical viewpoint directed solutions toward a system of two doors, while the operational viewpoint directed solutions toward an inclined ramp. A good choice should favor the operational considerations. Currently, without anticipating the solution that will finally be adopted for the vehicle, one can see clearly that the analysis carried out, supported by full-scale mock-up trials of the different designs, makes it possible to establish directions for the designer based on both technical and operational arguments.

ANALYSIS OF TASKS FOR A SIMILAR SYSTEM

Another step involves the analysis of tasks to determine the probable future activity of the operators in the planned system. This analysis can be performed in the abstract by considering the direct results of the analysis of requirements and the function analysis, but it can also be built in a comparative way by analyzing existing systems that provide a partial solution to the problems posed. Knowledge of equivalent systems can be of great help in this stage.

An example of this process can be found in the Nuclear, Biological, Chemical Reconnaissance Vehicle program (VAB Reco NBC), which is currently entering the production stage. In this case, the task analysis was conducted using elements representing parts of the future system, pulling together the principal components. This analysis included each member of the crew (four in all) and permitted a better organization of the operators at the heart of the system. In particular, certain constraints appeared to be defining ones for the technical system and motivated some major changes in the allocation of certain functions to one operator or another. Among these defining elements was the need for the commander of the vehicle to have at hand a control screen for the processes under way (which was not identified in the analysis of requirements or the function analysis). This constraint had important repercussions for the overall design for the system, as well as for the design for the commander's position.

This same approach is being applied in another context, directed at determining the actual constraints involved in personnel selection for

two systems under study (the Leclerc tank and the Tiger combat helicopter). Current research concerning the selection and training of pilots for the future Tiger, for example, leads us to consider in a global manner the problem of transfer of training. Should pilots be trained and then be given a conversion course for the new system, or should novice pilots be trained on the new system? The task analyses for two systems (the Gazelle, old and well known, and the Tiger, a future system still in the prototype stage) have brought out a number of differences between the two systems, due primarily to the technological differences between them. It seems that the distinction between the roles, not to say the functions, of the commander and the pilot is likely to be much more pronounced in the new system than in the old. This specialization may require different aptitudes for each member of the crew, depending on the overall mission to be accomplished.

RETROSPECTIVE FUNCTION ANALYSIS

The idea of retrospective function analysis, which we developed recently, is a mixture of work analysis and function analysis. This step is of interest when, for example, the aim is to partially automate or mechanize a task that is currently performed using manual tools but that involves major health risks.

The example presented here concerns mine-clearing operations performed by engineering sappers. In the first step, a detailed analysis of the work was undertaken, then the actions identified were translated into "solution" functions. We then searched to identify the function of the next highest level to which the solution function belonged. Next, we constructed a tree of the functions, moving up as high as possible to build the principal function. The latter was then broken down into possible solution functions. For example, we found a solution function "sweeping with the aid of a brush," and another solution function, "feeling the ground with the aid of a probe." These two functions had the goal of detecting and recognizing a mine in the ground. The question was posed whether it was possible to perform this detection and recognition in a single operation with the help of a tool handled from a distance. This work led us to develop a mechanical probe based on needles, which can be used from a distance away. Thus, it will be possible to gather in a single action the shape and other physical characteristics of an object.

This example shows how one can transform part of the mental process through which the sapper, by many probes of the ground, constructs a mental image to identify the objeet, by presenting the operator with an image giving form to the objeet.

MODELLING THE SCENARIO

Task analysis permits us to obtain an overall vision of the aetivity of operators at the heart of any particular system. It then becomes feasible, when one is able to eharacterize precisely each task and the links between tasks, to create a functional model of the overall system through the appropriate simulation tools. Such modelling is available with tools like MicroSAINT, which we have been using for scveral years in this type of proeess.

The results obtained permit us to validate the initial alloeation of funetions and the division of tasks between human and maehine as well as the arrangement of the tasks, and also to know the influence of variations in the parameters of certain tasks (duration, typc of link, lcvel of the task, etc.) on the overall performance of the system. In thc case of the VAB Reco NBC, such modclling permitted us to validate the target duration of a single mission of the vehicle, for which the initial characteristies had been estimated (but not cntirely on thc basis of tcchnical information or known operations) and to show that modifications should be made. In fact, in the first simulations made, the workload of certain operators was close to 100 percent, while others had a very limited workload. A bettcr division of functions permitted us to reduce this differenee.

MODELLING WORKSTATIONS

Another aspect of modelling environmental constraints concerns thc geometry and dimensions of workstations. Several points can be made about this process. The principal point concerns the geometrical modelling of the human operator, entirely separate from the work situation in which the operator is involvcd. Such modclling makes it possible to determine anthropometric constraints and dimensions based on the anthropometry of thc subjects and on thc specific population from which the users are drawn. We ean also extraet the postures, the constraints on rcach, and thc constraints on vision from thc anthropometry of thc sub-

jects or from the dimensions of the workstations themselves. For this analysis, we use a computer program for human modelling (Safework) that allows the creation of manikins that can be adjusted at will, as well as the creation (or the importation from a CAD system) of workplace details. The manikins thus created can be positioned in their working environment in a simple, intuitive manner. It is therefore easy to check or to validate, depending on the case, the suitability of the proposed technical solutions. This approach has been used for several different projects, such as the command post vehicle (VAB SIR), for example, for which a detailed analysis of the working environment of the operators is in progress. In this case, we have demonstrated the postural constraints associated with the design of the commander's position and the radio operator's position. This analysis allows us to provide guidance for designs that influence the overall activity of the operators and, in the end, the efficiency of the design itself. The designer can thus reassess certain elements of the design and seek solutions that are more optimal.

RAPID PROTOTYPING

Even further along in the process of defining designs and optimizing the allocation of functions at the heart of a weapon system, today virtual reality permits us to simulate, in "real size" and at less cost, complex situations in which the operator is an indispensable element in the control loop. It is possible to define a virtual environment in enough detail to give a certain realism to the simulation generated, and to permit the operator to carry out drills in a configuration close to that of the future system. Nevertheless, one must beware of hasty interpretations of the results of such experiments, since it is not always easy to confirm the validity of the situation simulated with respect to reality. One must also take into account problems of transfer of training in the performance of tasks in the two different worlds, the virtual world and the real world.

COMPUTER DIRECTION OF MANIKINS (MicroSAINT)

Finally, other operators can be incorporated into simulations such as those described above using manikins directed by tools that generate scenarios. This is one route we are exploring at the moment. Our prin-

cipal objective is to be able to direct a Safework manikin, for example, using behavioral data provided by MicroSAINT or other products. We envision primarily: data on human movement; data on the physical effort the operator can exert; or data on mechanical constraints placed on operators in the execution of their tasks (in terms of postural stability). We will thus have access to the ultimate phase of simulation, which will permit: validation of the processes for allocation of functions at the heart of the system being designed; knowledge of the interplay, in real time, among the ensemble of situations and behaviors, which will allow the functioning of the system to be understood; and the extraction of important strengths and weaknesses in design solutions. This seems very futuristic now, but it is the promise offered by the possibilities of technology in the very near term.

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DISCUSSION AND CONCLUSIONS

The aims of the Workshop on Improving Function Allocation for Integrated Systems Design were:

- to review the need for function allocation;
- to review the maturity of available techniques and to make recommendations to human factors practitioners;
- to identify the need for additional research in the area.

The need for function allocation and the maturity of available techniques were addressed in the discussions that concluded each paper session. A final discussion session was used to identify promising developments in function allocation and topics for further research.

THE NEED FOR FUNCTION ALLOCATION

The workshop participants endorsed the importance of function allocation to the system development process. Function allocation decisions define the roles, functions, and tasks performed by human operators and maintainers.

Thus, function allocation is related to issues of automation and personnel reduction, as well as to questions about human responsibility for the safe and effective operation of a system. The steadily improving capabilities of hardware and software complicate decisions about how to balance human factors considerations against political, financial, managerial, and performance constraints. A formal review of those issues is essential, and function allocation provides that review.

Function allocation issues involve many criteria, including: the number of personnel and their rank, experience, and training; technical

feasibility, costs, and subsystem performance; and commercial, legal, and cultural constraints.

Workshop participants recognized that function allocation is a design solution which is achieved as part of the creative process in developing a system design. This solution includes expectancies about how the system will perform. Such expectancies must be tested, the consequences for the human operator must be evaluated, and the allocation of functions reviewed and revised in a tightly coupled, iterative process.

MATURITY OF TECHNIQUES

Overall, the workshop papers demonstrated that human factors engineering issues associated with function allocation are being recognized and that current human factors engineering techniques are being applied. If one judges by the papers, however, little research activity is being devoted currently to human behavior in systems operation or to improving human factors engineering techniques.

For example, no new major developments in function allocation were reported at the workshop, although several potentially promising means for improving function allocation decisions were mentioned in the discussions. These included the application of principles used in computer science for the allocation of functions in distributed software systems. Other principles might be available from resource allocation techniques used for factory and plant layout and production line scheduling.

The approaches to making function allocation decisions that were reported at the workshop included:

- a simple dichotomous choice between human and machine;
- a two-stage allocation process;
- iterative modification of function allocations; and
- reverse engineering of operator tasks.

The criteria that participants reported they had used for making function allocation decisions fell into the categories of performance, cost, technical feasibility, and health and safety. These criteria are recommended already in the human factors literature. Teamwork was highlighted as an important criterion in some presentations and discussions. The need to achieve a dynamic allocation of functions was supported by reports that "static" allocations of function do not work well in some

systems. This is because there are changes in the allocation of functions between team operators during long missions. Many operational systems involve missions lasting several days, and a single, static allocation of functions is inappropriate for such systems.

Overall, most approaches to function allocation reported at the workshop focused on evaluating the implications of the allocation decision for system performance and operator workload, rather than on making the decision itself.

This may reflect predictive weakness in available function allocation techniques; more likely, it reflects the many criteria that are involved in the decision. A function allocation decision can be evaluated only in the context of its consequences for the operator's tasks, workload, and resulting performance. Methods that were reviewed for evaluating implications of function allocation decisions included:

- fast-time computer simulations of operator tasks and workload;
- human-in-the-loop simulation;
- rapid prototyping; and
- virtual-reality prototyping.

RECOMMENDATIONS TO PRACTITIONERS

The following recommendations to practitioners were enumerated during the discussions.

1. Function allocation is essentially a creative process associated with the design of a system. As such, function allocation does not lend itself to a mechanistic approach or to automation, although computer-based tools can facilitate the process.

2. It is important that human factors specialists establish their methodology for implementing function allocation within the constraints posed by a particular project. Integrated design teams such as those described in the paper by McDaniel provide the working climate necessary for the early and effective interchange of data and concepts on the role of the human.

3. To assist the interchange of such data and concepts, practitioners should select approaches to function allocation that are understandable by systems engineers and designers. Because computer scientists, systems engineers, and human factors specialists use the term *function*

allocation to denote different activities, and because the terms *function* and *task* have different meanings depending on the user, practitioners should employ clearly understood, common definitions of such terms.

4. No one function allocation technique can be recommended for use by practitioners. Several viable approaches for function allocation are available and can contribute to the development of advanced systems provided they are applied at the correct point in the systems engineering process.

NEED FOR RESEARCH

The workshop generated a number of suggestions for research, as follows.

1. A high priority was assigned to research leading to the development of a taxonomy of function allocation issues. The goal would be to produce a taxonomy relating three aspects of function allocation: the problem domain, the criteria involved in function allocation, and the techniques appropriate to function allocation in that domain. The problem domain would cover: the type of system, whether human/human, human/machine, machine/machine; the system functions; and the function allocations. The criteria involved in function allocation would include political, organizational, technical, and financial aspects of the system. The appropriate techniques should encompass an essential set of paper-and-pencil techniques as well as emerging technology such as virtual prototyping. This research will also require the compilation of lessons learned from function allocation.

2. A suggestion related to the development of the above taxonomy was the need for research to understand the creative aspects of the design process that apply to complex systems.

3. Recommendations for the development of improved methods of function allocation included the use of genetic algorithms. Such algorithms can optimize a function when an explicit model is lacking. They might be used to optimize the human-machine system by linking operator capabilities to system functions.

4. A high priority was placed on research into predicting and measuring operator workload; this emphasis reflects the importance of testing or evaluating function allocation decisions. Such research should investigate a number of topics, including:

- the use of human-in-the-loop part-task simulation;
- the use of computer simulations of networks of operator tasks for representing human behavior (skill, rule, and knowledge based);
- the validity of current workload prediction techniques;
- the relationship of operator workload to system performance; and
- the validity of extrapolating from such predictions to conclusions about system performance.

5. A high priority was also given to research related to adaptive allocation of functions. The function allocation process has to cater to crew systems in which operators may pass responsibility for specific functions from one to another.

6. The function allocation process must also cater to the adaptive allocation of functions between humans and machines. Modeling of the operator to permit function reallocation based on the machine's model of the operator was seen as an important research topic; decision aiding was another.

7. One of the major research issues raised in the discussions was the role of humans in advanced systems. How should humans and machines work together collaboratively? Questions posed by Fitts and his colleagues in 1951 still lack general answers. Should the human monitor the system, given that humans are poor monitors? Should the system monitor the human? If so, what roles should humans play and what are their responsibilities? Are humans included in systems just to deal with those functions that engineers cannot automate? Opinions on decision making ranged from the principle that the human should make all decisions, because humans are responsible for systems, to the principle that there are some decisions that humans should never be permitted to make. For example, the "20 minute rule" prevents humans from intervening for 20 minutes in the event of the activation of the automatic-safety system of a nuclear power station.

8. There are ethical issues associated with these questions that are particularly important in the design of weapon systems. "Human failures" such as recent well-publicized incidents in which friendly forces or noncombatants have been attacked can be attributed to, and are considered to be the responsibility of, the command chain. To whom should the failure of a highly automated system be attributed when that system is designed to modify its behavior on the basis of experience and the

specific situation being played out? This question deserves more attention from all those responsible for the development and procurement of advanced weapon systems.

CONCLUSIONS AND RECOMMENDATIONS

- Because the human operator is increasingly a limited and expensive resource, and because the human elements have a large influence on system life-cycle costs and system effectiveness, the allocation of functions between humans and machines is of major concern in the design of advanced systems.
- Function allocation is not an isolated activity, but is intrinsic to an iterative process of analysis/design/evaluation for developing human-machine systems. Function allocation must be incorporated into the development process early enough to influence design decisions and to permit iteration.
- No single technique is available that deals with all of the issues involved in assigning functions to humans. Function allocation includes issues of: system effectiveness; reliability; cost; feasible level of automation; personnel selection, training, and experience; team effectiveness; and economic, political, and cultural constraints.
- Because available allocation techniques are essentially qualitative, function allocation decisions must be validated by predictions of operator workload or system performance, and the allocation decisions revised if necessary. Within the iterative design process, function allocation itself must be iterated to evaluate and refine the decisions made.
- Research is required to support the development of a taxonomy of function allocation issues that relates factors affecting function allocation to the problem domain and to available function allocation techniques.
- To provide more rigorous means of validating function allocation decisions, research is needed into: the validity of current workload prediction techniques; the relationship of workload to system performance; the use of computer simulations of networks of operator tasks; the validity of extrapolating from such predictions to conclu-

sions about system performance; and the potential of virtual reality simulations for validating design decisions.

- The development of advanced technology involving decision aids and/or autonomous decision subsystems poses problems concerning the roles and functions of humans that are not fully understood at this time. Caution must be exercised in the implementation of such technology.

Appendix I

SOME BASIC QUESTIONS IN DESIGNING AN AIR-NAVIGATION AND TRAFFIC-CONTROL SYSTEM[1]

In planning a long-range research program on human factors in air-navigation and traffic control, it is necessary to make some *predications* about the role human beings will play in the system of the futurc. This is obviously a very difficult kind of forecasting to do, but the things that psychologists know about human capabilities and limitations enable us to make some general statements on this point. Consideration of this very basic question will also point up some important problems for future research.

POSSIBLE ROLES OF THE HUMAN OPERATOR IN FUTURE AIR-TRAFFIC-CONTROL AND NAVIGATION SYSTEMS

One way of approaching this problem of forecasting the directions of future developments is to ask: ***What roles can the human be* assigned in *future systems?*** Four possible kinds of control systems, distinguished in terms of the degree of human participation in the control process, can be postulated. We list these only in order to illustrate the range of possibilities. We do not wish to imply that they all are equally feasible or desirable.

1. Fully Automatic Control. To some people automatic flight and automatic traffic control appears to be the direction that future developments will take. Our society is continually becoming more highly

[1] From *Human engineering for an effective air-navigation and traffic-control system* (pp. 31-56), by P. M. Fitts (Ed.), 1951, Washington, DC: National Research Council.

mechanized. Automatic machinery opens doors for us; enables us to communicate with each other in a matter of seconds though we may be separated by miles; provides signals for our rail and highway traffic; and solves mathematical and logical problems of such speed that the layman's imagination is overwhelmed. If this is the ultimate direction in which air navigation and traffic control developments will go, then there will be no human operators in the control system of the future, and human-engineering will be concerned with problems of production and maintenance, rather operational problems.

2. *Automatic Control with Human Monitoring.* Another possibility is that human operators will always have to be around to take over in an emergency even though the equipment be fully automatic. Machines are not infallible. Dial telephone systems, for example, sometimes break down—tubes burn out, relays need replacing, wires deteriorate. Even if the primary task of the human becomes that of monitoring, maintaining, and calibrating automatic machines, some men will need to be capable of making intelligent decisions and taking quick action in cases of machine breakdown or in unforeseen emergencies.

The human-engineering research problems relating to such a control system would center about the capabilities of the human as a monitor, as a trouble-detector, and as an emergency controller, both on the ground and in the air.

3. *Semi-Automatic Control Supplemented by Human Performance of Critical Functions.* Another possibility is that the human may routinely perform certain critical functions, leaving the major work of the system to semi-automatic machinery. If this turns out to be the case, then long-range research on human functions would center about those higher-level mental functions we call reasoning, judgment, planning, and decision making. It would emphasize the problems of information display and communication.

4. *Primary Control by Human Operators Who Would be Assisted by Effective Data-Analysis, Data-Transmission, and Data-Display Equipment.* Still another possibility that we must consider is that the role of the human in the future traffic-control system will resemble the role he performs at present. Human operators may do most of the critical tasks—sizing up display information, receiving and issuing communications, making decisions, and issuing directions—aided by much better data-displays, communication links, computers, and other equipment, than present-day controllers have.

DIVISION OF RESPONSIBILITY BETWEEN MEN AND MACHINES

Some general answers to the problem of deciding the proper role of human operators in a control system can be made on the basis of what psychologists know at the present time about the limiting characteristics of human capacity and performance.

In some cases, our information on these points is fairly complete; in others, we must characterize the statements as being little better than informed opinions. In discussing these broad questions we have attempted to indicate what answers are based on well-established experimental evidence, and what on informed opinion.

SOME GENERAL CHARACTERISTICS OF HUMAN PERFORMANCE THAT HELP DEFINE THE ROLE OF THE HUMAN

Alertness. In considering the possible role of the human in an air-navigation and traffic-control system we know that certain allocations of responsibility would not be desirable because of human limitations. The second alternative listed above, automatic control with human monitoring, often might not work well because there is evidence that in certain kinds of tasks humans are poor monitors. In tasks that call for long periods of relative inactivity, humans tend to become inattentive, and bored, and sometimes fall asleep *(see Mackworth, 1948, 1950).* Even if the system were arranged to force the attention of the human monitor at the time of equipment failure, his immediate reactions might be far from adequate.

One premise we have assumed in considering this kind of system is that the human should be prepared to take over critical functions of air-traffic control in case of emergency. But a man cannot make intelligent decisions in an emergency unless he has an adequate understanding of the traffic picture at the moment of the emergency and for a short time preceding it.

Thus, we are forced to conclude that the monitor must keep alert and thoroughly informed of the traffic situation at all times in order that he can take over in emergencies. we must also conclude that a monitoring

system is one of the worst kinds of work situations when we want the human to stay alert.

The railroads long ago separated the functions of expediting traffic and of monitoring for possible collisions, giving responsibility for the former to men and for the latter primarily to automatic machines.

It is true, of course, that men do perform many monitoring tasks in modern industry. Electrical substations, for example, are monitored by men. Also, even though men may be inherently poor monitors it is possible that in certain special cases they might be more dependable monitors than machines.

Considerations such as these lead us to the following two conclusions which we believe to be well supported by present knowledge: *(1) Human tasks should provide activity.* The roles of the human operators in the future air navigation and traffic control system should be active rather than passive ones. Activity in any task is conducive to alertness, and helps to insure that the human will keep abreast of the situation. Activity also is conducive to learning and maintenance of proficiency. *(2) Human tasks should be intrinsically interesting.* The role of the human in any system should be intrinsically interesting in order for human efficiency to remain at a high level. Although there is no simple set of rules for making human jobs interesting, a great deal that we already know can be applied to this problem.

Overloading. A second consideration relating to the role of the human operator is the question of whether humans or machines should be assigned to tasks in which they may be "ganged up on" or overloaded. Our information here is very sketchy indeed. We do know that humans are notoriously variable in their behavior under conditions of extreme stress. Some break down completely; others turn out a creditable performance even under exceedingly adverse conditions. However, complex machines may also break down under such conditions.

There is some evidence to suggest that under overload conditions a human, in some ways, performs better than does a machine. Under disaster conditions, as an illustration, automatic dial telephone systems are known to have broken down completely under overload conditions when, according to informed opinions, human switchboard operators would have been able to get at least some calls through. Whether this is a universal generalization we can make about comparative man-machine performance is highly problematical, but we should at least not discard

completely the idea that in some ways humans may function better than machines under stress conditions.

Fallibility. The final consideration which needs mention is the relative fallibility of a man to a machine. Machines are by no means infallible, but in general they can be made to carry out specific functions with fewer errors than would be made by humans. This raises the question of whether safety should depend on human alertness and decision making or on automatic machines. Our answer to this is an unqualified assertion that the primary responsibility for safety in air traffic control should not rest primarily on humans. This leads to another important working principle.

It is our conclusion, based on what we know about human abilities, that as a rule machines should monitor men. We suggest as an important working principle that checking, verifying, and monitoring equipment be devised that will make it impossible for any human in an aircraft or on the ground to violate basic safety rules, such as assigning two aircraft to the same block of space. This is the reverse of the commonly-expressed idea that men should monitor machines. We are suggesting that in general machines should monitor humans.

WHAT CAN MEN DO BETTER THAN MACHINES?

In our search for a general answer to the problem of dividing responsibility between men and machines, it would help us considerably if we could find some general answers to the problem of what people can do better than machines, and vice versa. A listing of those respects in which human capabilities surpass those of machines must, of course, be hedged with the statement that we cannot foresee what machines can be built to do in the future.

1. Sensory functions. One respect in which human capacities often surpass those of instruments is in the sensory functions. This is especially true of absolute sensory thresholds, i.e. the minimum absolute energy necessary for sensory detection. The human eye, for example, is capable of detecting the flare of a match 15 miles away on a dark night. It can detect the presence of a black wire, 1/16th inch in diameter, viewed against the clear sky a quarter of a mile away. The human ear is so sensitive that it can almost detect the random collisions of molecules of air. It is far more efficient at low energy levels than any existing microphone. On the other hand, machines can be designed to respond to en-

ergy outside the wavelength bands to which our eyes and ears are sensitive. We shall not dwell on this prohlem any longer except to point out that psychologists, physiologists, and physicists have accumulated a vast amount of basic information ahout human sensory capacities. It is one of the areas in which many facts are known. Design engineers who have particular prohlems in this area can easily secure the information they need by consulting industrial or engineering psychologists. *(See, for example, the Tufts College Handbook of Human Engineering Data.)*

2. *Perceptual abilities.* Closely related to the above is the superiority of the human in perceptual abilities, particularly with regard to what psychologists call *stimulus generalization.* As an illustration, nearly every time you see your car you see it under varying conditions of illuminations, with varying amounts of dust on it, and from different angles. Yet you ordinarily have no difficulty at all in distinguishing it from other cars. In other words, you generalize your memory of your own car and recognize it even though the energy pattern acting on your eyes is always different. Abstract conceptual qualities like squareness, roundness, triangularity, are easily grasped and used hy the normal person even though triangles, for example, come in an infinitude of shapes. We should note that engineers have not succeeded in producing instruments which have the versatility of the human in these eapaeities. *The conclusion here is that a human is very good at sizing up complex situations quickly, especially if data are encoded and displayed in such a way that he can use perceptual capacity to the maximum (i.e. if adequate "pictorial" or familiar "patterned" displays are used.)*

3. *Flexibility.* Another special capacity of the human is his extraordinary flexibility and ahility to improvise. These abilities are still incompletely understood by psychologists, but they represent important respeets in which humans surpass machines. The amount of flexihility a machine has is fixed hy the amount that was huilt into it. The maehine will attempt as many different kinds of solutions as its designer planned for and no more. Experiments on complex problem-solving in humans, on the other hand, show that humans may attempt many different solutions for the same prohlem—just think of the numher of ways in which this paragraph could have been written to convey essentially the same point. Flexihility is especially important in a changing and evolving system, such as one in which new techniques are constantly coming into use. It also provides insurance against complete hreakdown in

emergencies. *The conclusion here is that if flexibility in a system is important, it probably is a good plan to let human beings play an important role in the system.*

4. Judgment and Selective Recall. The nebulous ability we call judgment also appears to be unique in the human. In large part, judgment is due to the superior ability of the human to store large amounts of information and to pull appropriate information out of long-term storage at the appropriate time. This is what we ordinarily call memory. People do not remember everything they see, hear, or learn: but the things that are remembered are somehow integrated with the mass of material already there and are available for recall years later.

Good judgment is a crystallization based on experiences which resemble, but are not quite the same as, the situation facing a person now. An experienced controller may have an emergency situation which is not exactly like any other emergency he has ever seen. But if he has been properly selected and trained, he is capable of drawing upon similar experiences he has seen, or merely heard about, and of exercising good judgment in facing the present emergency. This kind of ability has not yet been built into a machine.

Machines can be constructed with memories, it is true, but the machines so far devised are not very efficient at the kind of selective, long-term storage needed in handling unique problems. *The conclusion here is that to the degree that we fail to reduce all operations to logical, pre-set procedures, we need people around who can make judgments.*

5. Reasoning. As we shall see later, automatic computers are superior in speed and accuracy to human brains in **deductive reasoning**, but no success has been attained in constructing a machine which can perform **inductive reasoning**. Inductive reasoning is that peculiar ability which mathematicians and scientists use when they formulate new principles on the basis of masses of empirical data. The original idea that formed the basis for Einstein's theory is an example of inductive reasoning although many of the later refinements of the theory probably have resulted from the process of deduction.

In summary then, we can see that the human carries within him some remarkable powers that cannot yet be duplicated by machines, especially abilities needed to deal with changing situations and unforeseen problems.

WHAT CAN MACHINES DO BETTER THAN MEN?

Humans, however, do have many faults as well as good points and it behooves us to list these as well. In general, machines excel humans in the kinds of things we have already turned over to them in our society—especially tasks requiring great strength, and tasks of a very routine nature.

1. Speed and Power. Although machines do not have many of the sensory and perceptual capacities that humans do, they far excel people in the ability to respond quickly and powerfully. Even under ideal conditions a man requires over 0.1 second before he can start to move a control in response to a signal, while in most normal work situations his lag time is even longer. Milton and others (1947), for example, measured pilot reaction time in the air and found an average lag of 1.55 seconds before they initiated a movement in instrument recovery problems. The time was 1.35 seconds for contact recoveries. In these experiments pilots were blindfolded and disoriented, then shown either their instrument panel or the ground and asked to re-orient and level the aircraft. An auto pilot would, of course, respond much more quickly. Machines can be devised to make movements smoother, faster, and with greater power than humans.

2. Routine Work. Machines excel humans in **repetitive, routine tasks**. Machines can be counted on to make fewer errors in routine tasks, and to turn out responses that not only are quicker, but are far more uniform than a person can make. They also do not become bored and inattentive.

3. Computation. Machines are more efficient computers than humans—no matter whether the computations are simple or complex. In the latter case, a machine can examine all the possible deductions from sets of postulates, reject those which are invalid, and act upon those which are valid. It is important to remember, however, that the rules of operation, the postulates, must be built into the machine.

4. Short-term Storage. Machines appear to excel humans in short-term memory. There are many jobs in our present society that call for short-term storage of information, followed by complete erasure of the data in preparation for another task. Machines can be built with this kind of memory. Humans, on the other hand, are not so good at it. They especially have difficulty in completely erasing information in short-term storage. Also, it is sometimes difficult to be sure that a man has

noticed and remembered a particular fact—this is why controllers often ask pilots to verify that they have understood certain critical information.

5. Simultaneous Activities. Finally, a complex machine is capable of carrying on more different activities simultaneously than is a single human being. We are talking here about decisions and activities requiring some degree of attention—not reflex or automatic processes like breathing. There is much information to indicate that when he has to employ his highest intellectual abilities man is essentially a one-channel computer—he can only work effectively at solving one problem or attending to one thing at a time. Only when activities have been greatly over-learned can he do several things at once very effectively and even then he may actually have to shift back and forth rapidly between the two activities. The only way to get around this human limitation is by adding more men to do the job.

These are some of the things we can say with confidence about the relative abilities of men and machines. They provide a starting point. However, it is obvious that we need much more information of this sort—more specific information about human capabilities and limitations in performing different tasks—before we can determine the optimum division of labor between men and machines.

We turn next to the question of division of responsibility between different human beings in the air navigation and traffic-control system.

DIVISION OF PRIMARY RESPONSIBILITY BETWEEN HUMAN OPERATORS

In any efficient air-navigation and traffic-control system there must be a clear division of primary responsibilities between the different human beings in the system. The exact nature of their responsibilities cannot be determined without knowledge of the equipment in the system; nor can the nature of the equipment that will give optimum system performance be determined without some consideration of what the responsibilities of various human beings will be. Very little research data are available as a guide to decisions of this sort. However, some general principles can be suggested on the basis of what we know about human characteristics.

How to divide responsibility between all of the people working on the ground versus all of those working in the air is a very important

matter. It is also a very difficult problem to answer. The techniques of systems research, which are discussed in a later section, can be applied to this kind of problem.

This particular problem is so broad, however, that it will be very difficult even by these techniques to secure conclusive answers. Among the difficulties confronting the research worker are those of changing operational conditions, or even of simulating different conditions, in order to try out different allocations of responsibility. It will also be very difficult to insure that each condition is tried out impartially and the results measured objectively. It is our conclusion that extensive use should be made of expert consultants, including Industrial Psychologists and Engineering Psychologists, in arriving at decisions about the allocation of major responsibilities of this sort. Research on certain aspects of the general problem is also indicated.

The problems of allocating responsibilities within a group of different human operators doing closely related tasks are similar to those just considered. These problems include the division of work load between a pilot and co-pilot, or between two ground controllers. In this case, it will be easier to conduct systems research. The systems to be studied are smaller and this makes simulation, systematic variation, and measurement easier. Problems at this level, whether they involve operational procedures, human-engineering improvements, or requirements for future equipment, can usually be studied by the technique outlined in the later section on systems research.

Fortunately, we already know a good deal about some of the factors that determine how many and what kinds of things one individual can do, and there are a few general rules for dividing responsibilities between different men, and between men and machines. Here are two useful principles.

1. Who should make decisions. Other things being equal, the person who is informed is obviously the best person to make decisions. A related principle is that decisions should be made near the point where basic information is derived—thus minimizing extensive communication links. Pilots have direct access to local air-derived information, such as data about the aircraft's altitude, about operating conditions about icing conditions, and about the amount of gasoline remaining. They are the logical people to make on-the-spot flight and navigation decisions. Ground controllers have direct access to ground-derived and ground-stored information. They are informed about meteorological

conditions, traffic loads, and schedules over a wide area. They are the logical people to plan, coordinate, and expedite the flow of traffic. In both cases, however they should have all possible aid in analysis and computation, whether this is accomplished by other men or by machines. Data-gathering and decision-making should be carefully coordinated.

2. *Equalizing work loads.* Usually the most effective division of responsibility, is one in which the work load is equitably shared by associated workers. The future traffic-control system must not overload the single pilot of a jet fighter, but at the same time it should permit efficient use of several persons on large transports. Often problems of work assignment can be clarified by determining the number of different tasks performed by a particular person and the relative importance of each task. The pilot who is making an instrument approach, for example, is a very busy man.

Two methods have been developed recently for reducing the work load of the pilot in this particular situation. One method is for a radar *(GCA)* operator on the ground to monitor the plane's position in azimuth and in elevation during its approach and periodically to give the pilot headings and rates of descent to fly. This relieves the pilot of one series of activities, that of cross-checking course-deviation and heading and deciding which heading to fly.

The other method is to provide the pilot with an airborne computer of the "Zero Reader" type that will tell him what bank and pitch changes to make from moment to moment in order to stay on the correct approach path. Other ways of simplifying the pilot's task during an instrument approach are undoubtedly possible. The point here is that we cannot expect a system to work if we overload one man.

SOME IMPORTANT ISSUES NOT DIRECTLY DEALT WITH IN THIS REPORT

This is a good place to mention several issues that are of importance for human engineering, but are not directly dealt with in this report.

Technical Feasibility

Research in human engineering should keep abreast of new engineering techniques, and new equipment developments if it is to foresee hu-

man operator problems and provide information in time to influence the design of new items. Although this kind of background information has been considered in preparing the present report, it is not discussed explicitly.

Economic Issues

Decisions about what human operators will do and what machines will do in any particular system involve balancing the increases in safety and efficiency against monetary costs. For any fixed amount of money that can be invested in a man-machine system there is probably a unique combination of human and machine elements that will maximize efficiency. Human-engineering research can furnish part of the data needed to determine this optimum combination, but again, we have avoided any discussion of these economic problems.

Manpower and Other Personnel Problems

Many different human activities are involved in designing, producing, and maintaining a man-machine system as well as in operating it.

Training. Manpower costs include those of training. Training costs may be high or low, depending on the design characteristics of the equipment that men must learn to operate. As an illustration, our analysis of present air-route-traffic-control centers revealed wide dissatisfaction with the new flight progress boards. In most centers these boards are arranged in such a way that the assistant cannot see what the controller is doing. For this reason he cannot assist the controller in many important aspects of his work, and receives little on-the-job training as a controller. Because of this, the CAA may soon have to establish special schools for training controllers, whereas the older type of boards were well suited for in-service training. Similar problems arise whenever pilots or ground personnel are trained on the job. Training time is an important criterion for the design of many items of equipment.

Maintenance of Skills. Tasks can be set up so that human operators eventually become deficient in certain important skills which are infrequently used. As an illustration, a pilot who relies too much on the auto-pilot may lose some of his skill in manual control, or one who

routinely uses automatic landing equipment may lose his skill in making manual landings. This in turn creates special training problems, particularly training for emergency operations. We have not considered this problem directly, but it is another criterion for judging the goodness of equipment design.

Job Life. Still another aspect of the manpower problem is the effect that equipment design may have on the number of years during which a man can hold a particular job or series of related jobs. Most traffic controllers today believe that their jobs can be done only by fairly young men. Many controllers told us that fifteen years is considered a long time to work as a traffic controller. Also there are few opportunities for advancement. It is obviously a waste of manpower if workers become unable to hold their jobs after such a short work life, unless these workers can move on to other jobs where they can utilize their experience .

Equipment Maintenance and Calibration. All equipment, especially complex automatic equipment, requires human maintenance, calibration, and checking. It is obviously important to design equipment so that maintenance time is minimized, and few human errors are made in adjusting machines. In this connection we want to point out the similarity in consequence of calibration and maintenance errors on the one hand, and errors made by human beings using nonautomatic equipment, on the other hand. All sources of human error will not be eliminated by going over to automatic equipment.

Although this report does not deal in detail with these problems, all of the manpower and personnel factors mentioned above—initial training, maintenance of proficiency, life span of operators, and equipment maintenance—must be considered in planning for an efficient man-machine system. In this regard the research programs on personnel and training problems in aviation will contribute to the engineering development program.

SUMMARY

Men versus Machines. In this section we have considered the roles men and machines should have in the future air navigation and traffic control system. We have surveyed the kinds of things men can do better

than present-day machines, and vice versa. Humans appear to surpass present-day machines in respect to the following:

1. **Ability to detect small amount of visual or acoustic energy.**
2. **Ability to perceive patterns of light or sound.**
3. **Ability to improvise and use flexible procedures.**
4. **Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time.**
5. **Ability to reason inductively.**
6. **Ability to exercise judgment.**

Present-day machines appear to surpass humans in respect to the following:

1. **Ability to respond quickly to control signals, and to apply great force smoothly and precisely.**
2. **Ability to perform repetitive, routine tasks.**
3. **Ability to store information briefly and then to erase it completely.**
4. **Ability to reason deductively, including computational ability.**
5. **Ability to handle highly complex operations, i.e. to do many different things at once.**

Monitoring. We believe that men, on the whole, are poor monitors. We suggest that great caution be exercised in assuming that men can successfully monitor complex automatic machines and "take over" if the machine breaks down. We believe that engineers should seriously consider **systems in which machines would monitor men,** especially in respect to matters of safety, and prevent them from making serious mistakes.

Overloading. Both men and machines are likely to break down or become unstable if overloaded. Men are subject to emotional stress caused by personal problems and other off-the-job influences. However, it is possible that in some ways humans can do a better job than machines under overload, or stress, conditions arising on the job—at least they may supplement machines in this regard, especially in situations where flexibility is an asset.

Flexibility. One of the greatest benefits to be gained from including human elements in a system is increased flexibility in adapting to changing demands. A proficient and well-trained human operator usually can adapt readily to the introduction of new equipment, to the sudden failure of equipment, or to the occurrence of a unique and unforeseen problem. This particular human capacity can be utilized to the fullest only if the overall system is properly human-engineered.

Research Implications. Most of the general research objectives that we consider in the following sections are not tied to any particular assumption as to what the role of the human operator in the future air-navigation and traffic-control system will be.

In some cases this has prevented us from formulating research recommendations in as specific terms as we could have had we been concerned, for example, only with the present system.

Instead of trying to be unduly specific, we have tried to think in terms of functions that may be performed by human controllers in any system, In most cases, suggestions for research are slanted towards general human behavior in broad contexts. Information derived from such research programs will not only be applicable to equipment of a certain kind and date, but will anticipate problems and solutions in connection with future equipment.

RECOMMENDATION

It appears likely, that for a good many years to come, human beings will have intensive duties in relation to air navigation and traffic control. It is extremely important that sound decisions be made regarding what these duties should be. As we have indicated in the present chapter, many of the facts that we know about human beings are pertinent to decisions about the division of labor between men and machines. We suggest later (see Research Objective IX, Problem Area I[1]) that human engineering consultants can be of great assistance when plans for new systems are being made. Even though the problems are exceedingly broad, we believe that very worthwhile progress can be made by research

[1] *Editors' note:* This proposal for research deals with the utilization of human-engineering data; a proposed project would seek the help of experts in making decisions about how best to utilize human abilities in an air-navigation and traffic-control system.

in this area, especially by the systematic analysis of various kinds of data that are already available in aviation and in industry. Therefore, we recommend the following research objective:

Research Objective 1. Determination of the Relative Abilities of Men and Machines to Perform Critical Functions in Air-Navigation and Traffic-Control Systems.

Basic research should be supported to provide the principles on which decisions about the most effective roles of men and machines can be based. The decision to develop a machine that will reform a certain operation usually implies a prior decision that a machine can do the job better, faster, or more reliably than a man. At the recent time there are few rules that can be followed in reaching such decisions. Information is needed about such general topics as these:

a. What standards or norms of human performance can be expected when men are assigned certain air-navigation and traffic-control tasks and how much variability will there be between individuals in the performance of these tasks?

b. To what extent will the various human tasks require unusual human capacities, and long training programs?

c. How can human performance be measured in terms that will permit the meaningful comparison of the effectiveness of men and of particular machines when carrying out certain tasks?

Collection and synthesis of known facts about human abilities will help to establish some of the needed principles. Some of the information necessary for answering additional questions can be obtained from existing records or can be collected during routine operations. In other instances, it may be necessary to conduct extensive experiments to establish some of the principles that are needed in this area.

Illustrative Research Problems. In this report we have advanced arguments in support of the hypothesis that men cannot efficiently monitor automatic equipment. This hypothesis needs to be tested in various work situations, and it may be that the answer can be found by careful

surveys of typical industrial situations, such as power plants or military lookout posts, where men are now employed as monitors.

As another example, in this report we propose the hypothesis that under certain circumstances men may function better than machines under conditions of overload and stress. This hypothesis needs to be validated, and again the answers may be forthcoming from a careful analysis of records from the operation of automatic machinery, such as dial telephone systems, during wartime conditions, floods, partial power failures, etc.

REFERENCES

Mackworth, N. H. (1948). The breakdown of vigilance during prolonged visual search. *Quart. J. Psychol., 1*, 6-21.

Mackworth, N. H. (1950). *Researches on the measurement of human performance* (Special Report No. 268). London: Medical Research Council, HMSO. 156 pp.

Milton, G. A., Jones, R. E., Morris, J. B., and Fitts, P. M. (1947). *Pilot reaction time.* Memorandum Report No. TSEAA-694-13A. Dayton, Ohio: USAF Air Materiel Command.

Tufts College. (1949). *Handbook of human engineering data for design engineers.* Office of Naval Research Special Devices Center, Tech. Report No. SDC 199-1-1. Medford, Mass: Tufts College Institute for Applied Experimental Psychology.

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